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A Methodology to Create a Unified Trade-Off Environment for Advanced Aerospace Vehicle

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14. ABSTRACT

The development and implementation of advanced aerospace vehicles is an endeavor that can potentially affect long term aviation operations and future system capabilities for several decades. Selecting the best vehicle configuration(s) requires a thorough understanding of the capabilities and life-cycle considerations required by the end user, the vehicle's full spectrum operations, as well as technologies impacting both operational needs and system performance. The fundamental goal of the proposed effort involves using the Aerospace Systems Design Laboratory (ASDL) established expertise in the fields of decision support and advanced vehicle modeling and simulation (M&S) to develop an innovative trade-off environment for advanced vehicle concepts exploration.

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1. Introduction

The development and implementation of advanced aerospace vehicles is an endeavor that can potentially affect long term aviation operations and future system capabilities for several decades. Selecting the best vehicle configuration(s) requires a thorough understanding of the capabilities and life-cycle considerations required by the end user, the vehicle's full spectrum operations, as well as technologies impacting both operational needs and system performance. The fundamental goal of the proposed effort involves using the Aerospace Systems Design Laboratory (ASDL) established expertise in the fields of decision support and advanced vehicle modeling and simulation (M&S) to develop an innovative trade-off environment for advanced vehicle concepts exploration.

Over the span from October 2010 to September of 2015, a Capability Assessment and Trade-off Environment (CATE) with accompanying Excel tool was developed. The environment is powered by surrogate models created from the NASA Design and Analysis of Rotorcraft (NDARC) code. The surrogate models were created from data obtained through experiments performed in NDARC using candidate Joint Multi-role Rotorcraft configurations (Single Main Rotor, Compound, and Tilt-rotor). The use of surrogates for distinct concept families provides a novel way of doing rapid trades to investigate how performance and vehicle unit cost vary across the different designs. To assess technology impacts on vehicle capabilities, CATE includes an Interactive Reconfigurable Matrix of Alternatives (IRMA) that allows for input and management of technologies. CATE uses Quality Function Deployment style qualitative analysis for technologies that do not necessarily affect mission performance but do affect mission effectiveness. Users can assess technologies by manually selecting options using the IRMA or by using a genetic algorithm to perform a selection based on the user's objectives.[1]

This fiscal year work included building two new capabilities into CATE. Previously, the tool only assessed how technologies affect the sizing of a vehicle, which might reduce weight rather than expanding capabilities. A baseline + upgrade feature was implemented to assess how a technology would affect future performance of a vehicle without resizing, which allows for analyses of vehicles that will undergo several technological changes in its lifetime, such as the UH-60 Blackhawk. An initial step in providing Reliability, Availability, and Maintainability (RAM) analysis was made by incorporating a discrete event simulator as described below in Figure 1.

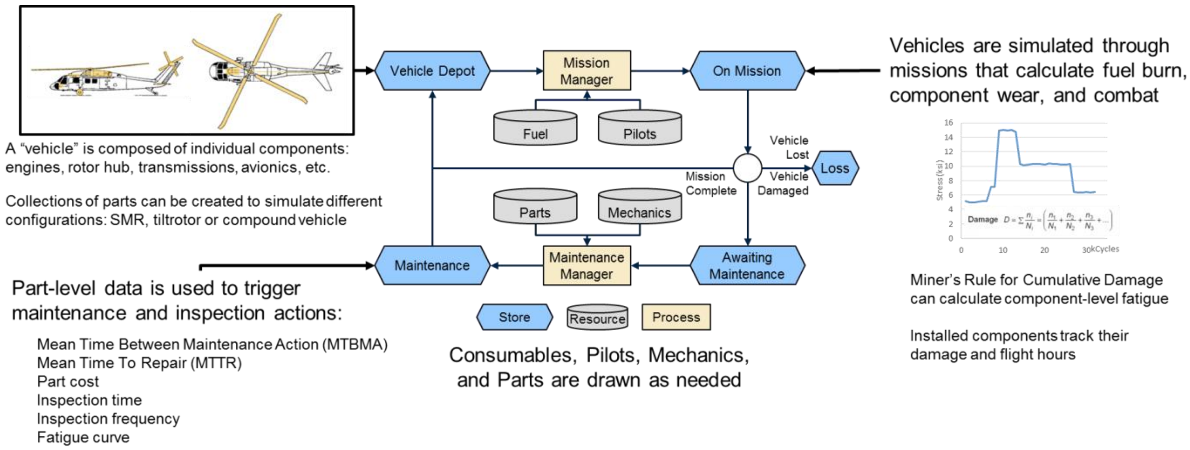

Figure 1. RAM Discrete Event Simulator

Many emerging technologies are support-related which cannot be captured in a performance analysis. Thus, the added RAM capability expands CATE's mission effectiveness analysis beyond a QFD style qualitative assessment. There is potential to further this effort to introduce more quantitative analyses of non-performance capabilities by integrating tools for life-cycle cost assessments and survivability.

In the previous year, a use case study was also performed with the tool to validate its processes and demonstrate how CATE supports decision makers. The tool was first used to demonstrate that it could accurately predict the performance improvements that the UH-60L upgrade offered compared to the UH-60A helicopter. Secondly, the tool was used to demonstrate how the wide chord blade technology would be represented in CATE in addition to predicting the capabilities the new system offered. This Use Case provides insights into the possible workflows for assessing technologies as well as the types of questions CATE currently answers.

During efforts to introduce more technologies into CATE's library, researchers encountered setbacks in technology representation. These issues with technology representation stem from relying on information from Subject Matter Experts (SMEs). Many previous studies with technology insertion, including ASDL's TIES methodology[2], suggest using the Delphi Method or other systematic processes for getting information from SMEs. SMEs give valuable insight based on in-depth knowledge and experience in the field. However, this information is subjective in nature and may be biased by the opinion of the SME. Previous efforts have also encountered issues interacting with SMEs, such as a need to educate SMEs on what technology k-factors are or issues with creating questionnaires that adequately draw information from the SME. These methods of interviewing SMEs generally require iterations between questioning and analyzing responses, which can be a long drawn out process due to the work involved in creating new questions and the time required for gathering responses. These issues can lead to work stoppages, especially if SMEs are difficult to get in touch with.

For technologies with abundant literature about their impacts, questioning SMEs may be avoided or may require fewer questionnaire iterations. However, for CATE to be easily utilized by researchers looking at the newest technologies, published information about these technologies may be difficult to ascertain. Therefore alternative methods should be utilized. Given the large body of work in the field on technology forecasting[3], there is potential for investigating and documenting heuristics for which methods work well and when to use them.

The current CATE environment provides an innovative methodology and tool for investigating the relationship of technology, mission requirements, and vehicle capabilities. Its current form easily gives useful insights on how technology affects performance. However, improvements in the methodology of technology representation and the types of analyses and trades the tool can perform will give decision makers the ability to answer more questions about their technologies and the advantages they offer. These capabilities will be increasingly necessary as efforts are made to evaluate the Future Vertical Lift (FVL) program and the technologies it incorporates.

2. Report on Work Completed

2.1 Assessment and Prototyping of a Server-Based CATE

This research was initiated to improve on the current state of CATE (Figure 2). As an Excel spreadsheet, the application combines Python code, VBA code, and multiple spreadsheets with Excel relationships between everything. This poses two issues. The first being it is extremely difficult for new developers to modify anything with all the different back-end languages and connections. The second issue is that the front-end design that Excel allows is very limited in terms of options and is very slow.

The server-based application of CATE (Figure 3) shows promise to improve the functionality and speed of the user interface while also providing a much more accessible back-end for outside developers to understand and modify. Moving the back-end code to PHP, Ruby, Python or Java makes back-end code more accessible and modifiable. At the same time, the front-end codes, HTML, CSS, and JavaScript, provide endless customization while also performing very quickly. Another advantage to the new server-based approach is that it is accessible anywhere and on any device, since it is run from a single server.

As it exists, the CATE server application is still in a development state and most development has been on the back-end preparing the data for use. The current features follow:

- Front End – What the user sees (slider tools, plots, comparisons)
    - HTML / CSS / JavaScript
    - Uses JavaScript UI API for interface
    - Ability to input individual sizing values accurately
    - Ability to upload sizing .csv files
    - Ability to set all parameters of SMR, Compound, and Tiltrotor to a single set
- Back End – Everything the user can't see (calculations, file management, etc.)
    - PHP / Java
    - Handles reading files (ex: SMR equations via .txt files)
    - Handles running .bash, .py files via command console (Windows only)
    - Runs NDARC via command console (Windows only)

The interface consists of two views: the input space and the output space. The input space consists of four tabs: one for each rotorcraft configuration and one for more functions and options (titled Tools) (Figure 1). Under each individual rotorcraft tab are sliders and input spaces for sizing parameters. Under the Tools tab are options for setting all three rotorcraft parameter sets to one parameter set and prompts for uploading sizing .csv files for individual rotorcraft. The output space currently displays surrogate sizing data, to be compared to NDARC exact values when integrated, visual graphs, representing the configuration sizing of each rotorcraft, and bar graphs, to compare any desired feature or sizing data.

The back-end of the site initializes by generating the interface through PHP template functions. Currently, the JavaScript file main.js handles all the data, but the heavy operations should be moved to PHP functions. This way, the server will take the processing load instead of the client so older computers and browsers don't suffer when using CATE. This will also allow client computers with varying operating systems to run CATE, not just windows. Running NDARC (and any .exe, .py, .bash, .filewrapper files) is handled through PHP, running the exec() function to run the command and output any files to their proper folders. The folder system is identical to the current CATE application, for ease of use when transitioning.

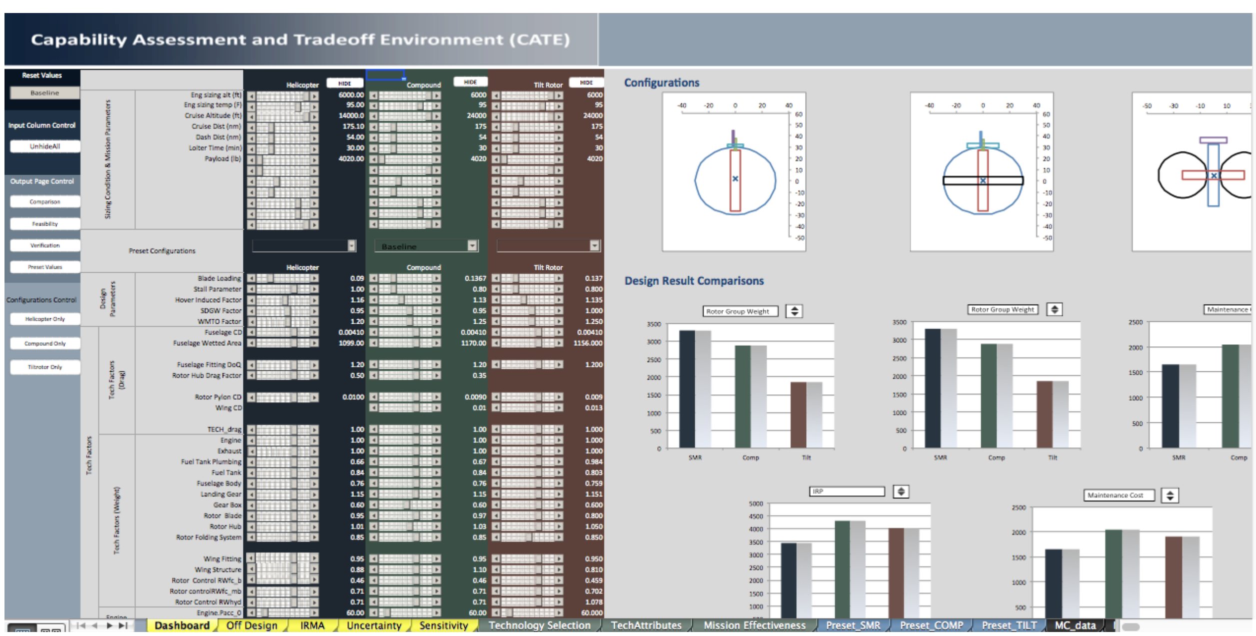

Figure 2. Current Excel Based CATE Interface

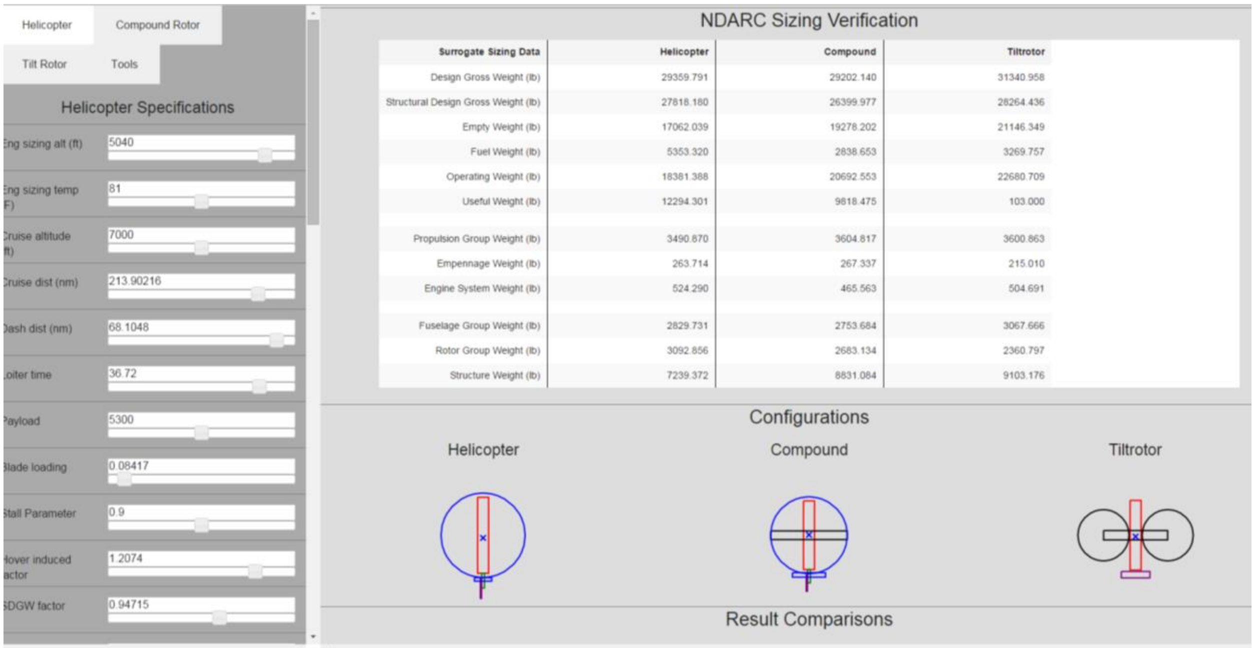

Figure 3. Server Based CATE Interface: the dark gray area to the left represents the input space, while the lighter gray area in the right 3/4 represents the output space.

Immediate next steps for the server-based CATE application will be to complete the implementation of data visualization, most importantly incorporating the feasibility contours. Some of this visualization, mission based sizing for instance, will require full implementation of NDARC and command line scripts. This will require creating individual functions to run command line scripts based on the required task. This will most likely be the most straight forward next step for the application. The important step before implementing command line tools fully will be setting up a Windows based server that has access to the command line.

Another option alternative to setting up a central server can be to bundle the software in an application, installing and running locally on machines. This also gives the option of versioning, taking out features one user doesn't require and keeping those features in for another. Running in a server-based environment, every aspect is completely customizable for optimal configuration. When developing the tools to run files through the command line, care needs to be taken to make sure the script is secure.

The current state of the CATE tool has led to the conclusion that a server based application would be better suited for the need, allowing remote access from a multitude of systems with faster run and response times all the while improving back-end user modification and endless interface customization. The current state of the server-application is a JavaScript file which relies on a Windows based server's ability to run the command line. To improve functionality and performance, this JavaScript file should be translated to PHP. Additionally, setting up the tool to operate on a UNIX based server would result in faster run times and easier modifications as the UNIX OS is better suited for servers.

2.2 Update CATE Environment to Latest NDARC Version

2.2.1 Update to NDARC 1.9

The main updates between NDARC 1.6 and 1.9 are changes in the maintenance cost models and change in the DoD inflation cost. Other updates include reordering the engine groups and propulsion groups in the vehicle definition files native to NDARC. However, these changes do not affect the performance.

Because CATE used the DoD inflation model, update to NDARC 1.9 modified the acquisition and maintenance cost output. Also, the update of the default cost maintenance model contributed to the change in maintenance cost output.

1.2.2.1 New maintenance cost model

In NDARC 1.6, the default maintenance cost model is the model based on *Harris and Scully,* that bases cost on weight empty and on power. In NDARD 1.9, a new model based on data by *Harris* was included, where maintenance cost is calculated from separate estimates of labor, parts (airframe, engine, and avionics), engine overhaul, and major periodic maintenance costs. It is important to note that both the *Harris* and *Harris and Scully* models are available in NDARC 1.9. Table 2 shows estimates of the maintenance cost from Harris and Harris and Scully for the preset SMR vehicle in NDARC 1.9.

1.2.2.2 New DoD inflation model

The inflation model cost included in CATE is the DoD inflation model. Between NDARC 1.6 and 1.9, the inflation tables were updated, leading to variation in the extrapolated costs. In order to illustrate this, aircraft acquisition cost and maintenance cost models were compared between NDARC 1.6 and NDARC 1.9. Note that in both versions, the maintenance cost models was selected as *Harris and Scully,* for comparison purposes.

1.2.2.3 NDARC 1.9 validation

In order to validate the new NDARC 1.9 with its previous versions and understand how the upgrade affects the results, efforts were invested to match the results between the two versions. Table 1 shows a comparison between sizing output from NDARC 1.6 and NDARC 1.9 for the preset SMR vehicle.

Table 2 shows the cost estimates using the different maintenance cost models but with the same inflation model (fixed to 105% with respect to year 2015). This highlights that new maintenance cost model (Harris) predicts a higher maintenance cost estimate for the preset JMR SMR vehicle.

When using the *Harris and Scully* maintenance cost (available in both NDARC 1.6 and 1.9) and when the inflation ratio is hardcoded to 5% i.e. when not using the DoD inflation model that has been modified between the two versions, every output variables matches exactly between the two versions (within 0.01%), as seen in Table 3. Consequently, it is concluded that the output given by both versions of NDARC are in good agreement with each other.

Table 1 Comparison between sizing output from NDARC 1.6 and NDARC 1.9 for the preset SMR vehicle with baseline values of inflation models (DoD) and maintenance cost models: NDARC 1.6 has Harris and Scully and NDARC 1.9 has Harris model.

Output variable	Unit	NDARC1.6	NDARC 1.9	Error
Design Gross Weight	lb	27206.94	27208.13	0.00%
Structural Design Gross Weight	lb	25846.59	25847.72	0.00%
Empty Weight	lb	17176.07	17176.76	0.00%
Fuel Weight	lb	4351.76	4352.26	0.01%
Operating Weight	lb	18510.83	18511.53	0.00%
Useful Load	lb	10030.87	10031.37	0.00%
Propulsion Group Weight	lb	3380.79	3381.07	0.01%
Empennage Weight	lb	229.07	229.09	0.01%
Engine System Weight	lb	466.66	466.69	0.01%
Fuselage Group Weight	lb	3093.66	3093.76	0.00%
Rotor Group Weight	lb	3130.95	3131.13	0.01%
Structure Weight	lb	7581.24	7581.58	0.00%
Main Rotor Radius	ft	29.43	29.43	0.00%
Main Rotor Solidity		0.12	0.12	0.00%
Aircraft Drag	ft^2	18.98	18.98	0.00%
Fuselage Drag	ft^2	4.51	4.51	0.00%
Main Rotor Hub Drag	ft^2	5.11	5.11	0.00%
Main Rotor Pylon Drag	ft^2	2.25	2.25	0.00%
Drive System Limit	hp	3911.49	3911.89	0.01%
CRP (per engine)	shp	3364.18	3364.52	0.01%
MRP (per engine)	shp	3210.20	3210.52	0.01%
TOP (per engine)	shp	3210.20	3210.52	0.01%
IRP (per engine)	shp	2998.65	2998.95	0.01%
MCP (per engine)	shp	2530.39	2530.64	0.01%
MCP SLS sfc		0.36	0.36	0.00%
Aircraft Cost	$M	22.93	23.14	0.91%
Maintenance Cost	$/hr	1515.71	2127.11	40.34%

Table 2 Comparison between NDARC 1.6 and NDARC for different maintenance cost models, but with a fixed inflation (105% with respect to year 2012) 1.6 has Harris and Scully maintenance cost, while 1.9 has Harris cost models.

Output variable	Unit	NDARC 1.6	NDARC 1.9	Error
Aircraft Cost	$M	18.63	18.63	0.01%
Maintenance Cost	$/hr	1182.04	1511.36	27.86%

Table 3 Comparison between NDARC 1.6 and NDARC 1.9 with a fixed inflation value (105% with respect to year 2012) and both with Harris and Scully maintenance cost model. Both versions return the same cost estimates.

Output variable	Unit	NDARC 1.6	NDARC 1.9	Error
Aircraft Cost	$M	18.63	18.63	0.01%
Maintenance Cost	$/hr	1182.04	1182.11	0.01%

1.2.2.4 Implementation

In the following sections of this report, the UH-60 test case is discussed. However, as pointed out in the following sections, the cost estimates were not studied. Because of the fact that performance estimates are the same for the SMR configuration between NDARC 1.6 and NDARC 1.9, the choice made no impact on the predictions. The latest version (1.9) has been used to complete the task of the following sections of the report.

2.2.2 Updated Surrogate Models

A new set of surrogate models was implemented in CATE. The surrogate models are used to efficiently and rapidly represent sizing of the rotorcraft from NDARC. While the previous version of CATE already contained surrogate models, the updated surrogates are different due to the fact that they contain different ranges on certain variables and that they were created with the calibrated UH-60A model (Section 2.5). Consequently, a new set of design cases were created and new surrogate models were created. A set of 2,500 points were created with a Latin Hypercube Design of Experiment and 2,500 points were randomly generated to compute model fit error. The input and output variables are illustrated in Table 4.

The update procedure in CATE was straightforward due to the presence of routines to allow updating the RSE (Update RSE1 button in the RSE1 tab). The RSE are saved as text files in the RSE folder of CATE, with the variables having the same variable names as used in CATE. The design variable bounds in the Dashboard tab (Columns AD-AF) were adjusted to the bounds used on the DOE. The preset inputs were also updated, as specified in the user manual. The technology selection models also can be updated by the "Update equations for new RSEs and variables" button of the IRMA_Calcs tab.

Out of the 5,000 points evaluated, 266 failed (5.3%), which was less than in the previous year's attempts (which was in the order of 10% failed cases). One of the factors that reduced the number of failed cases is a change in the convergence parameters.

Moreover, other points were removed because they represented sizing conditions that did not lead to relevant vehicle. In most cases, these vehicles exceeded by a factor of 3 the TOGW, the engine drive limit or the Fuel Weight of the UH-60A. These cases included for example low disk loading cases with high payload. These points included regions of the design space that were deemed not relevant to the tool. Removing such points also allowed having much better statistical predictions. It is important to note that removing those points might lead to errors when querying the surrogate model in the extremes of the design space. It was noted that in a future platform, the design space (input variables) could be have dynamic bounds, in other words, limits on specific variables could change as a function of the other variables' values. Because the Excel inputs assume a hyper-cubic design space, the current input bounds are simply static minimum and maximum. A web-based interface may facilitate more sophisticated methods of defining the design space.

Surrogate models were created using the generated cases. Based on previous years lessons learned and due to the need of Excel to use relatively simple equations, Response Surface Equations (RSEs) were used. Because all of the cross-terms cannot be used in a simple Excel cell due to the limit in length, a Step-wise regression was performed to keep the most relevant term. For each output variable, transformations were applied and 3 models were compared, based on their statistical measures (*R squared*). The model with the highest *R squared* was selected. The three models are linear (no transformation), logarithmic transformation and square root transformation. These modeled were used because they represented a simple and effective way to increase the statistical measures and were based on previous years surrogate model creation procedures.

Table 4: Surrogate model design variable

		Lower bound	Upper bound
Engine sizing and mission parameters	Eng sizing alt (ft)	0	6000
	Eng sizing temp (F)	59	103
	VROC	300	700
	VFWD	80	180
	hov time	0	40
	cr time	0	140
	Wpay	1000	3960
	P accessory	42	62
	Wcrew	400	1087
	ft hov time	0	40
	ft cr time	50	175
Design parameters	Blade Loading	0.06	0.116
	disk load	6	9
	log cg	0.06	0.09
	vtip	600	800
Tech (Drag)	Fuselage CD	0.006	0.009
	CD ff	0.006	0.009
	CD V fus	0.25	0.5
	CD MR hub	0.0015	0.005
	CD MR pylon	0.025	0.05
	CD TR hub	0.02	0.04
	tech drag MR	0.4	1.5
	tech drag TR	0.4	1.5
Tech (Weight)	Engine	0.7	1.1
	TECH_gb	0.4	1.3
	TECH_rs	0.7	1.6
	TECH_ds	0.5	1.3
	Fuselage Body	0.5313	0.8349
	Rotor Blade	0.5	1.5
	Rotor Control RWfc_b	0.3213	0.5049
	Rotor controlRWfc_mb	0.4984	0.7832
	Rotor Control RWhyd	0.4984	0.7832
Engine Tech	Engine.Pacc_0	42	187
	Engine.SP0C_tech	120	260
	Engine.sfc0C_tech	0.25039	0.39347

The new surrogates based on the UH-60A were successfully created and implemented in CATE. They differ to the previous surrogates in the new design variables used for their creation, the calibration around the UH-60A data, the use change in inflow update parameter and the use of NDARC 1.9 (note that the change in NDARC version had no impact on performance).

Compared to the previous years' models, they present inferior statistical measures and some outliers. While this is still under investigation, it was noted that the design variables bounds affect greatly the number of outliers and the statistical measures.

2.3 Update CATE with Baseline with Upgrade Analysis

The baseline with upgrade capability was integrated in a new tab of the CATE environment. This tab compares a baseline vehicle and the same baseline vehicle with a retrofitted upgrade. The new retrofitted vehicle represents a baseline vehicle with some of its components modified. Consequently, this process does not affect the sizing process but affects the performance.

Initially, three ways to evaluate performance upgrades were identified:

- Stand-alone NDARC performance evaluation
- Multiple stand-alone NDARC performance evaluation
- Creation of a performance surrogate model.

The stand-alone NDARC performance evaluation has been selected and integrated in CATE. In all three methods, the retrofitted upgrade is represented by a modification of the aircraft description file, and by running performance analysis with the new vehicle. The new components are represented as change in the vehicle weights and components drag translated in the typical Tech Factor values.

2.3.1 Single Stand-alone NDARC Performance Evaluation

This first method consists of running a performance evaluation case in NDARC. First, a sized aircraft is generated from the input of the sizing dashboard. Then, a performance evaluation in NDARC is executed on the sized vehicle. Finally, the new "vehicle with upgrade" files are generated from the baseline vehicle description files, with the user's prescribed modifications to some of its components drag or weight technology factors. The performance of the new vehicle is then compared to the performance of the baseline vehicle. A notional flowchart of the baseline with upgrade evaluation is shown in Figure 4.

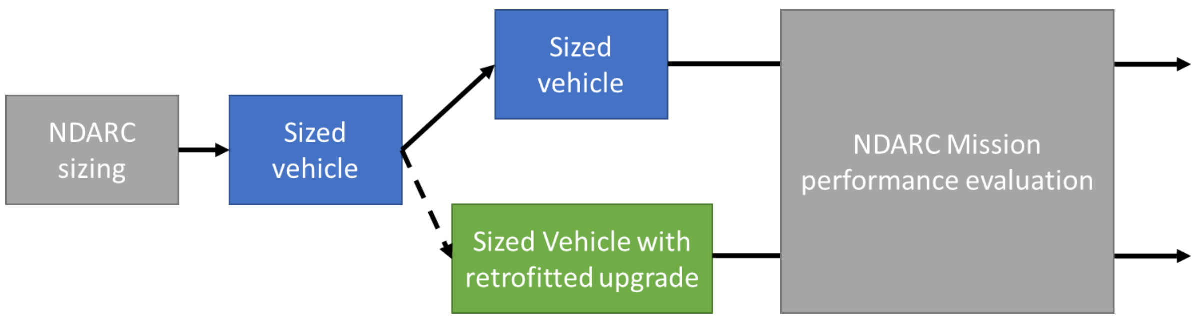

Figure 4. Notional Flowchart of the Baseline with Upgrade

This methods is a straightforward way to get direct information about the upgrade that requires three NDARC analyses (approximately 15 seconds total). Because the analysis is performed on the sized vehicle created by the user, this process can be applied to any vehicle. Moreover, because this step represents a Mission Performance analysis, some of the CATE functionality can be leveraged, namely the wrappers.

2.3.2 Multiple Stand-alone NDARC Performance Evaluation

Similarly to the first method, a sized vehicle is generated and is then evaluated in a performance evaluation run in NDARC. However, instead of analyzing a single upgraded vehicle, many performance runs can be performed, each run analyzing a different Technology Factor variable (drag or weight). By doing so it would be possible to get the local variation of the performance with respect to the possible input. A notional flowchart is illustrated in the Figure 5 below. The post processing represented in the figure could represent the creation of a function in Excel capable of returning the value of the some of the mission performance characteristics.

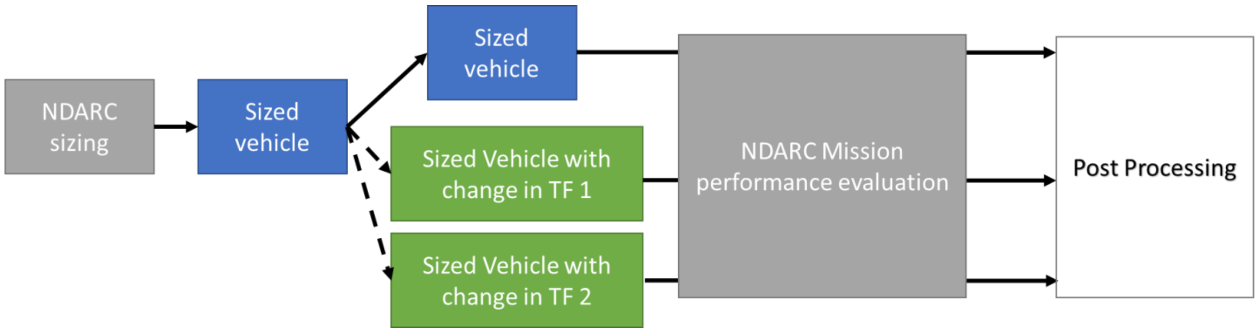

Figure 5. Notional Flowchart of the Multiple Stand-alone NDARC Performance Run

Similarly to the first proposed approach, the Multiple Stand-alone NDARC Performance Run can be applied on any vehicle previously sized and analyzed in the other dashboard. However, this second approach, depending on what is deemed relevant and how the post-processing is performed, could allow the user to visually see where performance gained could be achieved. This is due to the fact that there is not only information about a single performance case, but also some information about its variation about the technology factors. This method is a simplistic way to represent possibly complex relationship with respect to some of the variables. It would applicable only near the point analyzed and should not be extrapolated. Moreover, it would be based on the assumption that technologies or upgrades are additive, which might not necessarily be true. Finally, this analysis would represent 1-2minute of NDARC runtime.

2.3.3 Surrogate Model of the Performance

This last method consists of representing the performance of the vehicle as function of the upgrade parameters using surrogate models. Given a fixed aircraft baseline, the performance of the upgraded vehicle would be evaluated for a large set of technology factor combinations. Regressions could then be fitted to describe as accurately as possible the performance of the vehicle.

It is important to note that those surrogate models would represent the aircraft performance with under various upgrades, while the surrogates already implemented in CATE represent the vehicle characteristics with respect to a sizing task. Because the Baseline with Upgrade surrogate models evaluate the performance of a vehicle, they would be applicable to a single predefined vehicle (UH-60A for example), which could limit the relevance of this new tab.

However, since the surrogate models would represent completely the variation of the performance with respect to the upgrades, they would be applicable within the entire range of technology factors. They could be used to performed non-deterministic analysis of the upgrade as used in a technology selection decision process, similarly to how the IRMA uses the actual Sizing surrogate models.

2.3.4 Integration

The stand-alone NDARC performance evaluation has been selected and integrated in a new tab of the CATE tool. This method was selected as a good first approach to the concept of upgraded vehicle while leveraging some of the tools already available in CATE, namely the mission performance. It also offers the capacity to be adapted to any sized vehicle without an update of surrogate models, which was considered as an important element for this step.

A screenshot of the tool interface is shown in Figure 6. The user input is performed through slider bars, on the left of the tab, and the mission performance characteristics are plotted on the right.

Figure 6 Screenshot of the baseline with upgrade tab

On the input portion, the slider bars affect the drag and weight technology factors. The user can use the "Copy Baseline" button to use the same parameters as the baseline vehicle, and can modify specific technology factors to represent an upgrade.

These factors are the same as the factors present on the sizing tab. The user can decided to revert to the baseline values by using the “Copy Baseline” button or to modify some of the characteristics. The values that have been updated are highlighted in pink.

This new tab demonstrated the new upgrade analysis capability. While the results were very often very close to the results from the off design analysis, it was hard to conclude on how much the performance was affected by the new upgrade. Some future work could include a clearer comparison between the baseline and the baseline with upgrade vehicle.

This also opens up to the investigation of the other techniques of modeling the baseline with upgrade using Multiple Stand-alone NDARC Performance Evaluation or the Surrogate Model of the Performance. Both of these methods can provide more information about the design of the upgrades, and how to represent it could be analyzed.

2.4 Update CATE with Fleet Maintenance Modeling

2.4.1 Defining Objectives and Scope

One goal of CATE is to provide capabilities for evaluating technologies against well-defined attributes. For example, CATE currently has the capability of modeling technologies that impact performance, through technology factors on the NDARC metamodel. Technologies can be evaluated against quantitative performance metrics such as change in gross lift-off mass, installed power, etc.

One goal of CATE is to evaluate technologies that provide benefits beyond the flight performance and geometry characteristics of the vehicle, such as cost, combat effectiveness, or maintainability. These capabilities can currently be evaluated in CATE only through a qualitative assessment. Technologies are ranked using a relative scale according to a Quality Function Deployment (QFD) assessment, requiring close interactions with technologists and subject matter experts. Therefore, additional capabilities were investigated in order to provide quantitative evaluation.

Capability alternatives were identified based on their ability to model highly desired technologies. The Aviation Science & Technology Strategic Plan (ASSP) provides one survey of technology goals[4]. Capabilities were also identified from those currently in the CATE QFD and from discussions with the sponsor. The list of candidate capabilities is presented in Table 5.

Table 5: Additional Capability Options

CATE QFD	2014 Aviation S&T Plan	Other
Survivability	Affordability	Noise
Engagement and Effects	Deployability	Vibration
Navigation/Pilotage	Footprint	Mission Effectiveness
Situational Awareness	Availability	Crashworthiness
Communication	Situational Awareness	Detectability
Avionics Architecture	Battle Command	All-Weather Flight
Crew Station	Lethality	Life Cycle Cost
	Survivability and Safety	
	Mobility	
	Training	

For each of these capabilities, potential inputs, outputs, and modeling methods were detailed. These alternatives were then evaluated based on several characteristics. Capabilities measured by quantitative metrics would be most successfully integrated into CATE, and enable sensitivity analysis similar to the analysis performed on NDARC. Quantitative measures correspond to the use of physics- or logic-based models. These alternatives were also evaluated based on the availability of data to perform validation and verification. However, notional values can be used to perform validation of the model.

Based on these attributes, the vibration, availability, affordability, noise, and life cycle cost were identified as the strongest alternatives. These capabilities share a common thread of operations and support. The largest component of a system's life cycle cost is expended in the operations and support, popularly considered to be about 60% of the total system cost. O&S also constitutes the highest annual costs[5]. Maintenance modeling provides the capability of measuring metrics that overlap with affordability, availability, noise & detectability, and vibration.

The maintenance of a vehicle can be expressed in the metrics listed in Table 6. These metrics were determined from metrics identified by the ASSP report, and by similarity to contemporary maintenance literature [7][13].

Table 6: Maintenance Metrics

Metric	Units	Description
Mean Time Between Maintenance Actions (MTBMA)	h	The fleet-wide average length of time between successive maintenance actions, which informs the length of sorties, deployments, etc.
Mean Time to Repair (MTTR)	h	The fleet-wide average length of time required to perform a maintenance action.
Maintenance Man-Hours per Flight Hour (MMH/FH)	MMH/FH	The fleet-wide average number of hours spent on maintenance actions, inspections, etc. required for each flight hour flown.
Cost per Flight Hour	$/FH	The average recurring cost for each flight hour. This figure can be broken down into consumables, material, labor, facilities, etc.
Excess Availability	%	The proportion of time that the vehicle is fully operational but not in use.

The NDARC provides some estimates for purchase price, maintenance cost, and direct operating cost of shaft-driven helicopters and turboprop aircraft[6]. This model, based on the work of Harris and Scully, is a set of regressions based on weight, power, various binary configuration switches (e.g. turboprop vs. turbine, fixed landing gear vs. retractable, etc.), and calibration factors[7]. The effects of individual technologies must be represented by these vehicle-level calibration factors, which are difficult to determine for a new technology. A more suitable approach is to create a bottom-up estimate for the vehicle based on low-level technology effects that can be determined from prototyping or literature.

Furthermore, vehicle support occurs through discrete maintenance, inspection, and replacement actions that are either time-based (i.e. the replacement of a life-limited part or scheduled routine inspection), or event-based (i.e. post-flight inspection or the repair of a part damaged during combat)[8]. This nature makes maintenance modeling well suited to discrete event simulation (DES). DES condenses the simulation time by only performing calculations when a time- or event-based trigger is met, as opposed to a continuous system which must calculate every time step.

Utilizing DES would leverage past ASDL work into similar logistics and maintenance modeling[9,10]. The simulation code used for this project is an expansion of the code built for the model in[9]. The code is built in SimPy, an open-source library for Python. SimPy enables the execution of co-routines, trading control by the use of yield commands[11].

2.4.2 Model

The simulation is designed to model a fleet of helicopters at a forward base with some maintenance capacity. The simulation is composed of processes, stores, and resources as shown in Figure 7.

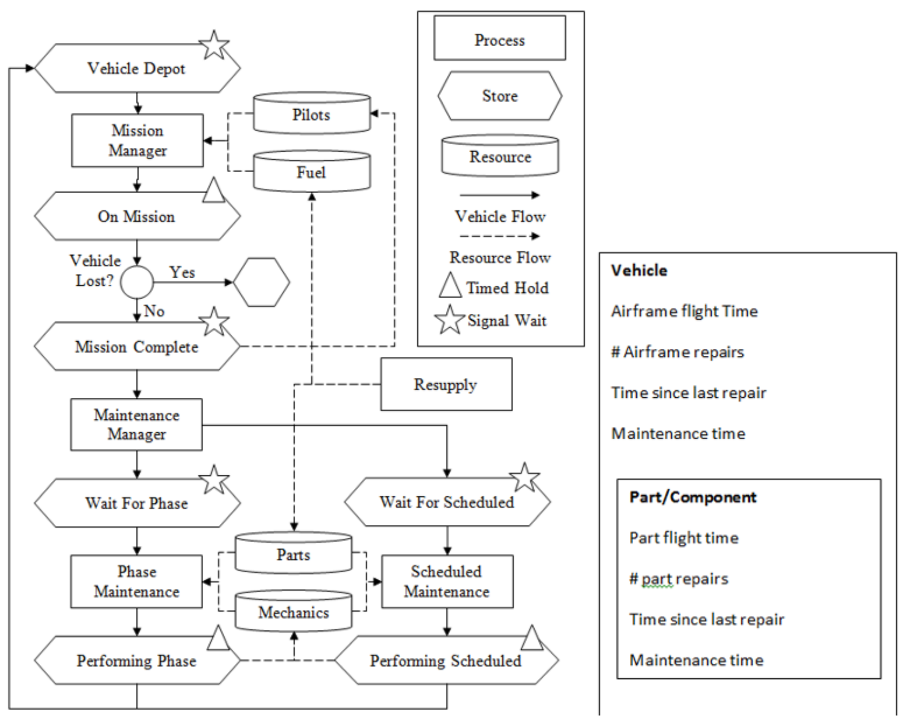

Figure 7: Rotorcraft Maintenance Simulation Flowchart

Vehicles pass through the simulation from store to store based on the decisions made by the processes. The Mission Manager determines when sorties are generated, randomly drawing these from a weighted list of missions. The sortie is then assigned to an available helicopter in the Vehicle Depot. The vehicle then undergoes preflight inspection and is allocated pilots and fuel. The Mission Manager may also trigger any outstanding maintenance items the vehicle has accumulated. For instance, if the sortie will cause a part to exceed its lifespan, the vehicle will be moved to maintenance, and another vehicle substituted on the mission.

Once the vehicle is on the mission, calculations are performed to determine if the vehicle successfully completes the mission, is damaged, or is lost due to part failure. Upon the vehicle's return, the Maintenance Manager determines whether the vehicle requires maintenance. If so, the vehicle is queued for the relevant maintenance actions, and is assigned parts and mechanics as they become available. Once the action is complete, the vehicle returns to the Vehicle Depot.

Pilots and Mechanics are returned to the resource once their mission or maintenance action end. Fuel and parts are not recycled, but are instead replenished periodically by resupply. Labor burden is calculated for pilots and mechanics during flight hours and maintenance hours, respectively. Burden includes pay and direct operating costs per person.

2.4.3 Parts

Each vehicle is constructed as a container that is filled with parts. Parts can be created for any system on the vehicle, such as an engine, a rotor blade, landing gear, etc. Because the vehicle is built from the component-level, many different configurations can be modeled by adding the relevant parts. A single main rotor can be modeled by including one main rotor part, or a tilt-rotor can be modeled by adding two props and the associated tilt mechanisms. The use of parts can also allow different levels of simulation, depending on the detail of the parts. At the highest levels, parts can act as entities like 'airframe,' 'rotor,' and 'engine,' but these can be decomposed into parts such as individual rotor blades, structural linkages, shafts, etc., to suit the model requirements.

Each part tracks its flight hours, damage, and total cost incurred throughout its lifetime. These metrics are calculated and updated according to the part's input value types, listed in Table 7.

Table 7: Part Input Variables

Input	Units	Description
MTTR	hours	mean time to repair the part, including uninstallation from the vehicle, repair to the component, and reinstallation
Inspection Time	hours	time required to perform a routine inspection on the component
Inspection Threshold	%	The cumulative damage threshold that will trigger component repair or replacement
Lifespan	hours	the flight hours allowed for a life-limited component
Unit Cost	k$	the purchase cost for a new component
Repair Cost	k$	the mean cost in material and specialized labor to repair the component
Failure Mode	'flight' or 'fatigue'	Determines how the model will track part usage and trigger maintenance. The model currently allows for calculation via cumulative damage, or flight hours
Failure Effect	'abort' 'loss' or 'continue'	This reflects the criticality of the parts. Parts may trigger no effect, mission abort, or loss of vehicle
Fatigue Properties	$\sigma = f(N)$	An S-N curve based on an aggregate of the part, or based on a limiting material. Stress as a function of cumulative number of cycles.

2.4.4 Mission Calculation

The mission includes performance calculation and part damage calculation. Equations from Leishman are used to calculate fuel burn and vehicle g-loading[12]. The vehicle speed is then used as the input to a vibration map in order to generate the vibration amplitude for use in part damage calculations. The vibration map is currently generated from Sikorsky flight data for the S-61, a vehicle with similar weight and dimensions to the UH-60[13]. If a part exceeds its damage threshold, the part ends the mission according to its Failure Effect. Missions can be successfully completed with or without damage, aborted with damage, or the vehicle can be lost.

2.4.5 Maintenance

Maintenance actions for each part can currently be triggered in one of two ways. Replacement or repair can be triggered simply by the part's total flight hours exceeding its lifespan. Alternatively, with additional information about the part's response to fatigue, part damage can be calculated via Miner's rule for cumulative damage[14]. Vibration and loading are calculated for each mission segment flown, and the results are used to increase the part's damage. This method assumes that the damage will be revealed by an inspection when the inspection threshold has been reached, and the part will fail once the damage reaches 1.0. This approach is best suited to parts that have a characteristic, homogenous component that is most susceptible to fatigue, such as a driveshaft or rotor blade linkage.

Vehicle-level maintenance actions are categorized into two groups: phase and scheduled maintenance. Phase maintenance is triggered after a number of flight hours. Scheduled maintenance occurs after set time intervals.

2.4.6 Technology Modeling

This model has the capability of representing technologies that impact vehicle parts, performance, and base maintenance practices through the use of k-factors. Performance factors include those on power, empty weight, figure of merit, and vibration magnitude.

Each part input can be modified based on the effect of a technology on its maintenance parameters. New parts may also be added to change the configuration to reflect the use of a technology. Factors also exist on vehicle-level maintenance and inspection.

2.4.7 Initial Results

In order to validate the model, a proof-of-concept was created using the UH-60M. Vehicle performance figures used in the mission calculation were taken from the NDARC UH-60M model used in CATE. The model vehicle was built from the following high-level parts:

Forward Airframe	Mission Equipment	Transmission
Center Airframe	External Supports	Hydraulics
Aft Airframe	Avionics	Fuel System
Tail Pylon	Engine	Flight Controls
Electronics	Main Rotor	Auxiliary Power Unit
Landing Gear	Control Rod	
Utilities	Tail Rotor	

The maintenance data for each of these parts was found from a Sikorsky report on the maintenance allocations and predictions for the UH-60M and HH-60M[15].

The simulation was performed varying the sortie rate for different fleet sizes and life-limited or active health monitoring (AHM) maintenance calculations for the engine part. AHM is simulated in the model by initiating maintenance actions based on the part reaching a threshold on its cumulative damage. The results for the excess availability are shown in Figure 8.

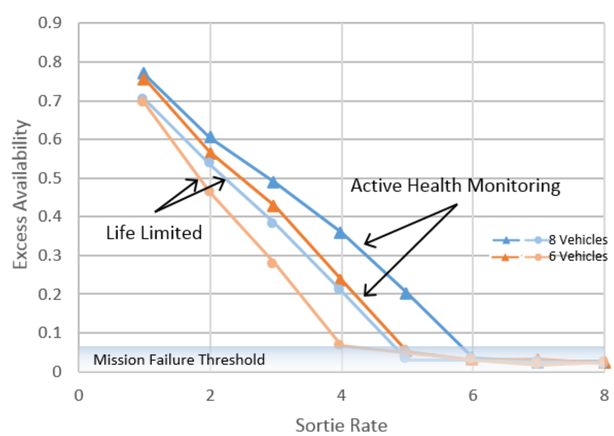

Figure 8: Excess Availability vs. Sortie Rate

The dominant trend of Figure 9 shows the inverse relationship between sortie rate and excess availability. Switching between life-limited maintenance and AHM has the effect of changing the overall MMH/FH, changing the slope of the line. The shape of these results can be compared to the results of Scott et. al., shown in Figure 9.

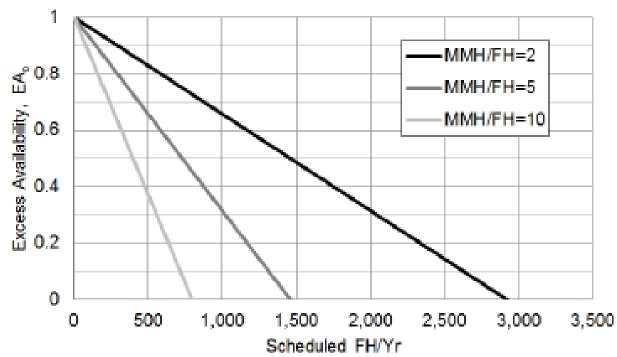

Figure 9: Excess Operational Availability vs. FH/yr for Varying MMH/FH[16]

While the work of Scott et. al. focuses on civilian rotorcraft, scheduled flight hours per year and sortie rate are both measures of demand, and therefore the same trend is expected.

2.4.8 Task Summary

The DES maintenance model has satisfied the objectives of increasing the capability of CATE and allowing technologies to be evaluated on additional attributes. The simulation outputs of availability and cost and time per flight hour add an operational dimension to the performance-based evaluation of NDARC, at a higher fidelity than the qualitative assessment currently used within CATE. Validation was performed using data from the UH-60M, demonstrating the expected relationship between maintenance activities and availability.

2.4.9 Forward Work

The DES is currently limited to accepting known input data for each of the components, which is only applicable to components and vehicles currently in use. However, the objective of CATE is to model technology use for future vehicles, for which detailed part information may not exist. This may be circumvented by using tech factors on the part-level inputs. However, each of these tech factors could be an alias of many different part properties, such as material, geometry, and design.

More detailed combat simulation can be added to the DES. Adding combat allows for modeling of additional technologies that contribute to combat effectiveness. Parts already have a variable that defines the failure effect, intended for use when a part reaches its damage threshold during flight. This could easily be used to represent damage during combat. Each part could also have individual vulnerability and susceptibility probabilities, representing their exposure and location within the vehicle.

Prior to integration into CATE, further verification and validation should be performed. The initial results using the UH-60 are suitable for verifying the model against the conceptual model and against previous work. However, validation would require using rotorcraft of different size and configuration.

Integrating the DES into CATE would allow both rapid analysis and point simulations to be run. In order to perform rapid analysis on many designs, a metamodel of the DES would be created. In the regression, the base variables such as number of mechanics, maintenance shop opening and closing times, etc, will be defaulted. The regression would be varied strictly over the vehicle parameters and tech factors. CATE would also include tabs for executing the DES directly, for the purposes of error determination or off-design analysis.

2.5 Develop Case Study with CATE around the UH-60 Blackhawk

Figure 10 depicts the process used to execute a case study on the UH-60A. The objective of the case study is to validate and demonstrate the use of CATE in a development process. First, a newly developed UH-60A NDARC model is calibrated and sent through the CATE surrogate modeling process to create a set of UH-60A surrogate models. Next, technologies are researched which distinguish the UH-60L from the UH-60A, and the UH-60M from the UH-60L. Then, the distinguishing technologies are represented in CATE using a previously developed technology representation process. Finally, two analyses are executed: sizing and performance analysis in CATE using the NDARC surrogate models, and a newly developed fleet maintenance modeling analysis for understanding the impact of technologies on vehicle capabilities not calculated in NDARC or CATE. Fleet maintenance is one of several “NDARC Non-capturables”; other non-capturables include survivability, communications, and situational awareness to name a few. The arrows represent the order in which these tasks are accomplished. The research and development related to creating the CATE spreadsheet tool are enclosed in the gold box. This spreadsheet tool is where both of the analyses occur to aid decision-making. The entire process is the “CATE process”, which is being validated and demonstrated. The colors of the boxes serve to distinguish which steps can be done concurrently and which steps must be done sequentially.

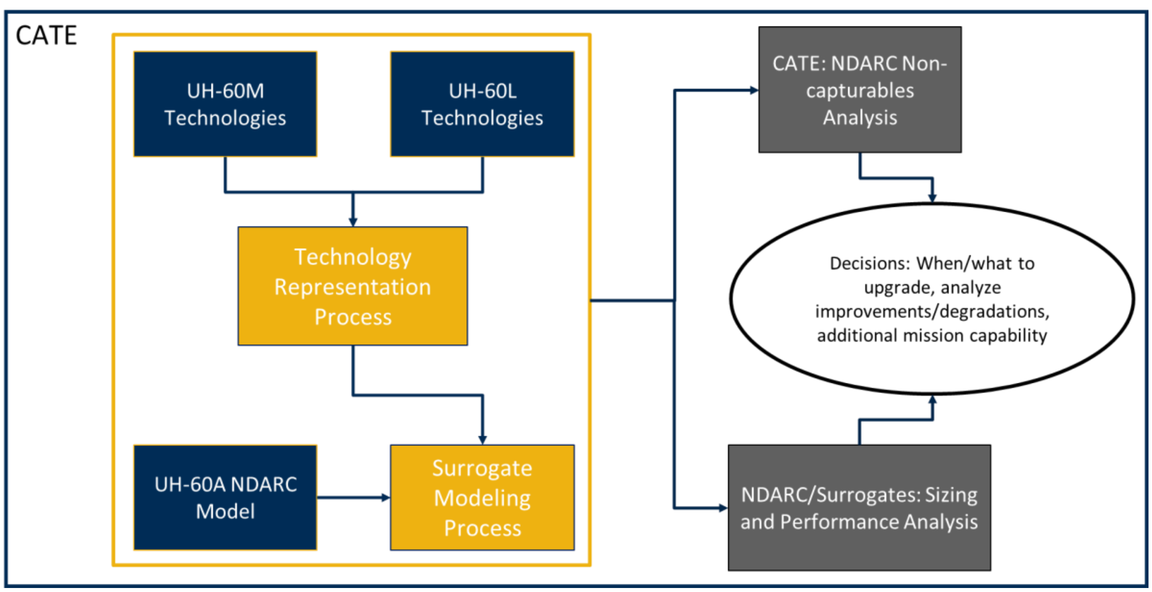

Figure 10. UH-60A Use Case Work Flow

Currently, the above process is unfinished as the fleet maintenance tool described in Section 2.4 is not exercised. However, many of CATE's other functions are exercised. The following sections will describe how the NDARC model is calibrated, how the technologies are analyzed and represented, and how CATE can be used to follow a development process.

2.5.1 UH-60A NDARC Model Calibration

This section covers the approach for creating a UH-60A model in NDARC that approximates the capabilities of the Black Hawk helicopter as well as the selection of technologies which represent the performance capabilities of the "L" and "M" upgrades. To accurately follow the development of the Black Hawk helicopters, a single main rotor model in NDARC that accurately represented the UH-60A is required. NDARC uses regression equations for aerodynamic and weight models which need to be calibrated to represent the UH-60A. Calibration is accomplished by changing the parameter values for these regressions. The NDARC performance analysis functionality is used to find the correct parameter settings for geometry, weight, power required, fuel flow, and power available. Using the performance analysis removes dependencies in sizing analysis on calculating the exact performance to get the correct weight output. Figure 11 outlines a systematic method for calibrating the groups of parameters such that effects of uncalibrated parameters are removed or minimized. The procedure starts at the inner loop and works its way out as geometry influences weight, which influences power required, which drives fuel flow.

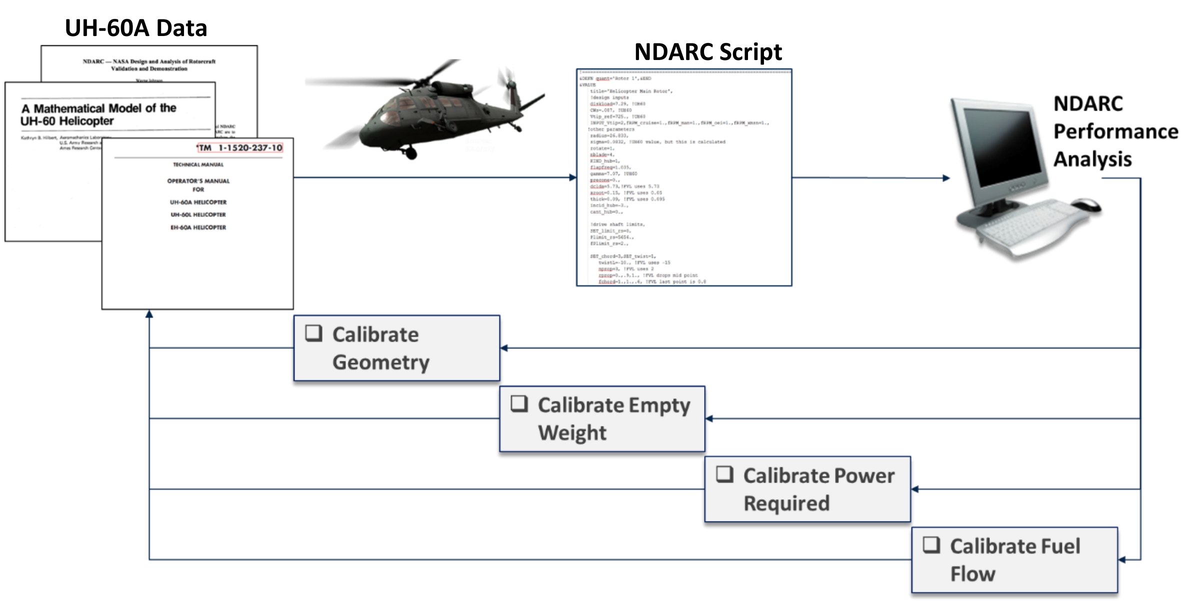

Figure 11. NDARC Model Calibration Procedure

A UH-60A model is developed by compiling information from multiple sources since no single source contained all information required to fully represent the UH-60A in NDARC. The NDARC script is modified from a SMR example packaged with the NDARC user training files[17]. Geometry for the UH-60A was derived using dimensions from the UH-60A mathematical model[18] and the UH-60A/L operator's manual[19]. Other vehicle information was taken from Johnson's *NDARC Validation and Demonstration*[20]. Empty weight was calibrated to the weight information for a manufactured UH-60A based on Sikorsky data[21] using technology factors. Power required data and fuel flow data were derived from the UH-60A/L operator's manual.

A model was created solely based on the information from NDARC validation paper[20] and the mathematical model[18]. However, this model was found to have excessive error in power required and estimating component weights. An attempt was made to retrieve the UH-60A NDARC model developed by Johnson for the NDARC validation paper, but the series of permissions that would be necessary to obtain the model made it apparent that creating our own model would be faster.

The NDARC calculations of power required were calibrated to the operator's manual data using a multi-step process described in the following two paragraphs. This process made use of techniques for creating surrogate models, such as variable screening, but rather than design space exploration, the intent was to find the parameter values for the regressed models in NDARC that best approximated the Black Hawk helicopter power required performance. This process was more complex than calibrating the geometry, empty weight, and fuel flow due to the large number of parameters (around 60) that could be used to modify the power required estimate.

A statistical screening was used to identify which parameters contributed the most to the variability of the output of power required in hover and in forward flight. The pool of parameters included all of the variables associated with induced and profile power for each rotor – main rotor and tail rotor. Large ranges of variation were given to all of the parameters. The NDARC performance evaluation took approximately a second to run, so an arbitrarily large number of cases could be used. A design of experiments (DOE) with around 4000 cases was chosen, which effectively covered the space given its size. ModelCenter's DOE tool[22] was used to select a 3721 run "Design Explorer Orthogonal Array" DOE supplemented with a 279 run Latin-Hypercube DOE.

Additionally, gross weight, velocity, and altitude were included in the analysis as blocking factors because data was taken from the operator's manual that corresponds for certain fixed weights, velocity, and altitude. Step-wise regression analysis was used to identify which parameters would be important. Two sets of parameters were identified using these step-wise regression models – a set for power required in hover and a set for power required in forward flight. See Appendix A – NDARC Calibration Parameters for a list of all possible parameters as well as the final set of parameters used for calibration.

Second, an optimization algorithm was used to find settings for the parameters previously identified. Any settings identified as not significant to the variability of power required (hover and forward flight) were defaulted to the SMR example setting packaged in the training files. The NSGA-II genetic algorithm was used to minimize the two objectives given below by varying the previously identified parameters.

1. Root mean squared error (RMSE) of power required to hover for gross weights between 12,000 lb and 21,000 lb, and at sea level standard (SLS) and 4000 ft, 95 ^{o}F
2. RMSE of power required in forward flight for set of forward speeds ranging from 0 to 155 kts at gross weights of 16,000 lb and 18,000 lb, and at SLS and 4000 ft, 95 ^{o}F

The range of gross weights for hover power required was selected to cover a wide design space: from near the UH-60A empty weight up to the UH-60A maximum take-off weight. The range of velocity for power required in forward flight was selected to cover the entire flight speed envelope of the UH-60A. The gross weights for the forward flight power required were chosen because the design gross weight (16,500 lb) fell between the power required curves for the two weights in the operator's manual (16,000 lb and 18,000 lb). See Figure 12 for an example plot from the operator's manual. Error in data retrieval was minimized by selecting points along these curves instead of interpolating between them. An example of the points chosen are indicated by red dots on the 10 ^{o}C plot in Figure 12. The velocities for these points were used for all the plots. The two altitude and temperature conditions were chosen because most performance estimations of the UH-60A are for these environments. The set of parameter settings chosen was the set that gave a minimum value of the sum of MSE_{hover} and $MSE_{forward\ velocity}$. This sum was chosen purely on engineering judgement and for simplicity. In retrospect, a better selection would be choosing the set closest in Euclidean distance to the minimum achieved MSE_{hover} and $MSE_{forward\ velocty}$. However, the error difference is likely to be marginal between these two methods of selection.

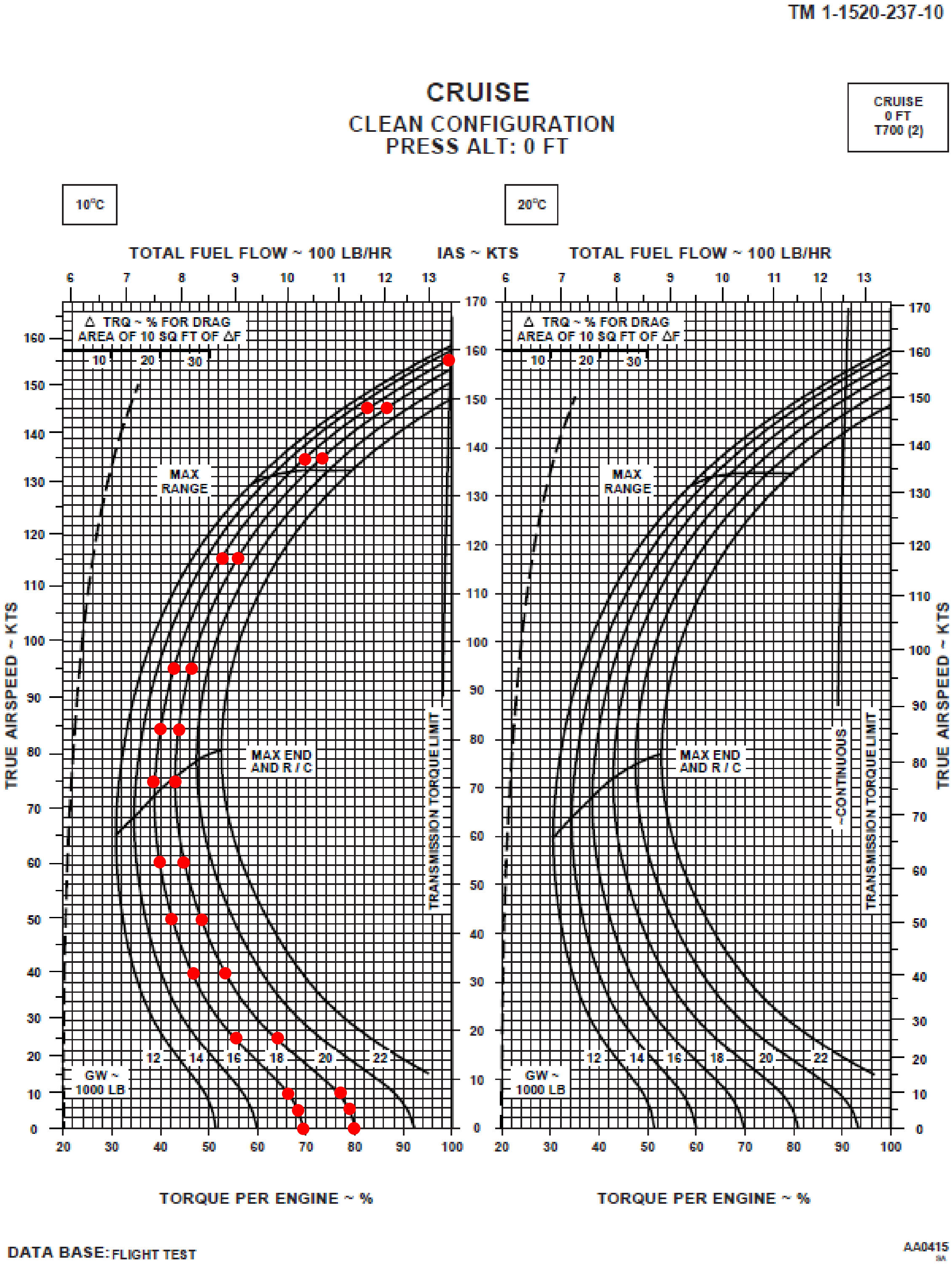

Figure 7-7. Cruise - Pressure Altitude Sea Level (Sheet 4 of 6)

7-19

Figure 12. Sample Cruise Chart from UH-60A/L operator's manual[19].

After the power required was calibrated, the fuel flow curve was calibrated to the fuel flow data from the operator's manual. Fuel flow is based on the power output of the engine, not the air speed of the vehicle. Therefore, so as to not double count the error in power required, a "truth function" was established to estimate the operator's manual fuel flow data for an input power setting. The power required and fuel flow data from the operator's manual was used to calculate a linear relationship between fuel flow and power required because the data exhibited linear behavior. Then the linear relationship was used to estimate the fuel flow data at each power required output of the NDARC model. Using this "truth function", the error in fuel flow calculations were calculated without additional error due to the power required calculation. The fuel flow error was then minimized by changing the scaling parameters in the referred parameter turboshaft engine model.

Figure 13 through Figure 22 indicate how well the power required and fuel flow output from NDARC matches the operator's manual data. These are actual values versus predicted plots. The closer to the line at 45^o the more accurate the NDARC model is. The images and RSME values indicate an acceptable fit. Data points for power required were visually selected so that the curvature was adequately captured, i.e. using more points in areas of high curvature along the power curve. Fuel flow data was taken for these same points.

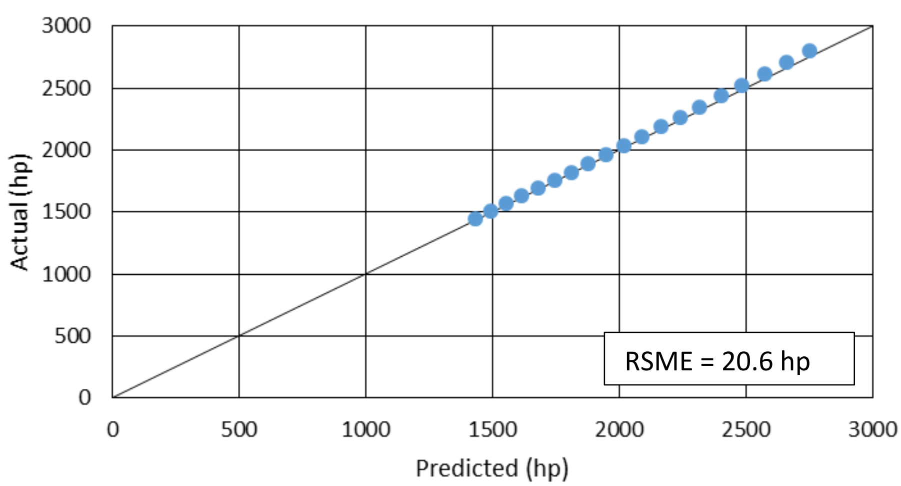

Figure 13. UH-60A Hover Power Required Actual vs Predicted at SLS

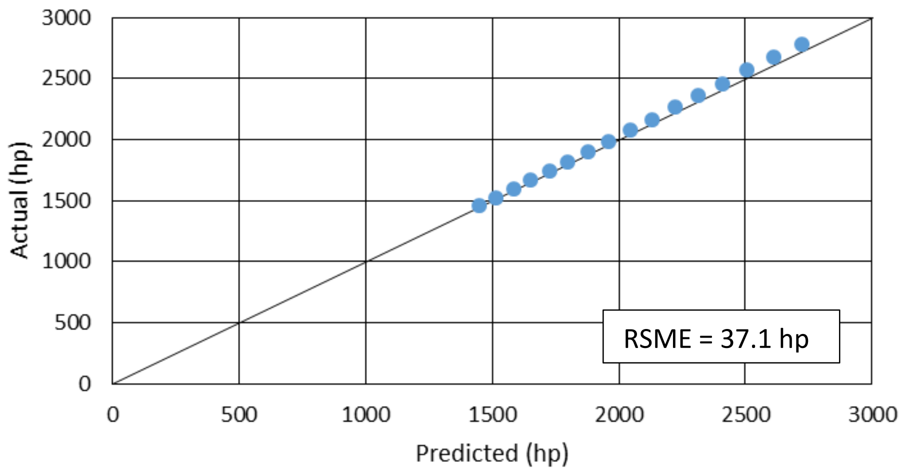

Figure 14. UH-60A Hover Power Required Actual vs Predicted at 4000 ft, 95 ^{o}F

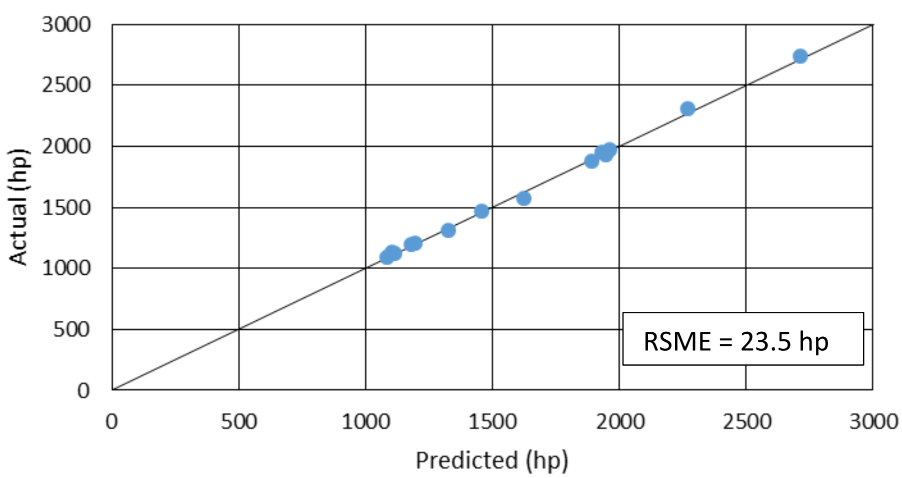

Figure 15. UH-60A Forward Flight Power Required Actual vs Predicted at SLS and 16,000 lb

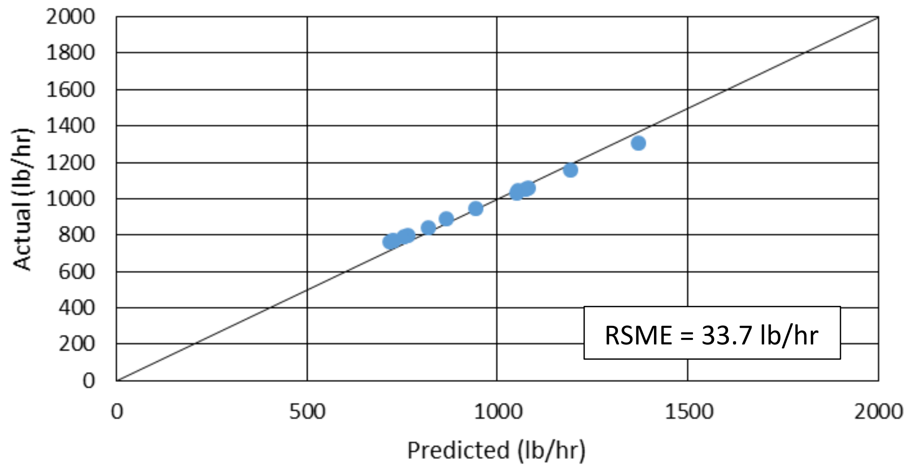

Figure 16. UH-60A Fuel Flow Actual vs Predicted at SLS and 16,000 lb

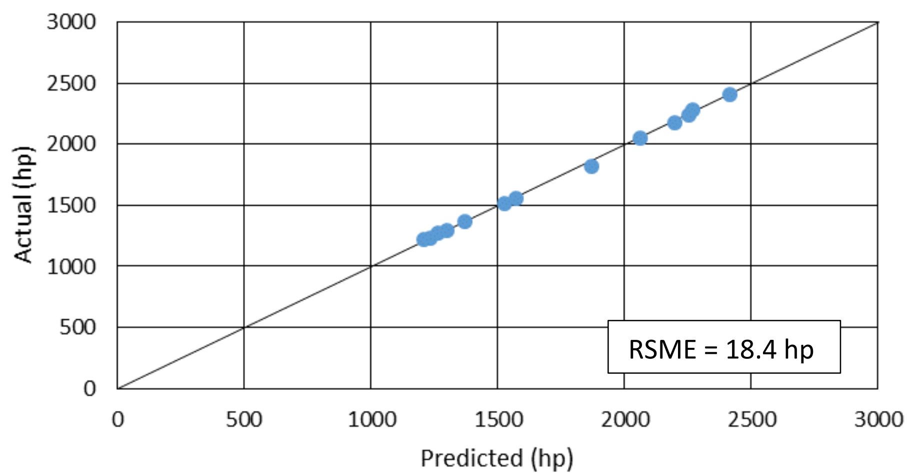

Figure 17. UH-60A Forward Flight Power Required Actual vs Predicted at SLS and 18,000 lb

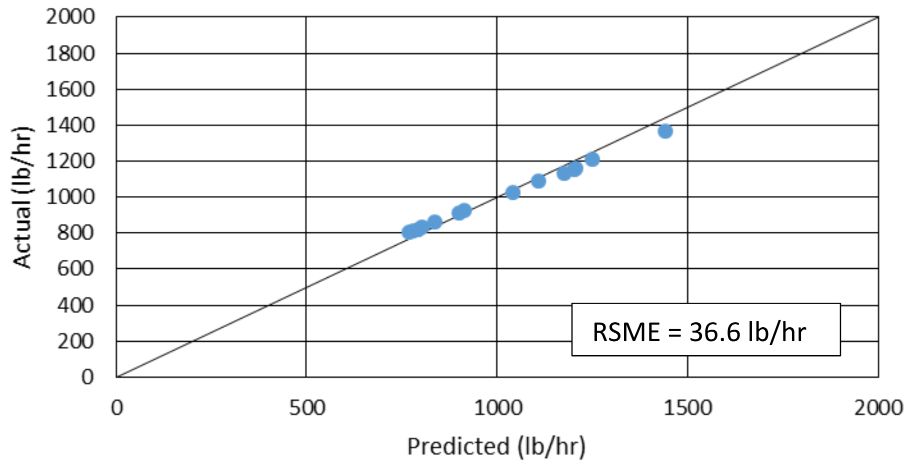

Figure 18. UH-60A Fuel Flow Actual vs Predicted at SLS and 18,000 lb

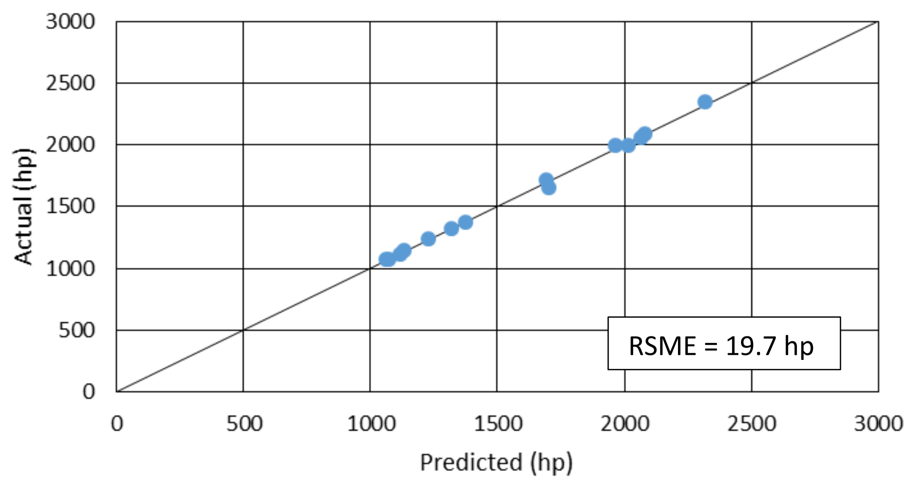

Figure 19. UH-60A Forward Flight Power Required Actual vs Predicted at 4000 ft, 95 °F and 16,000 lb

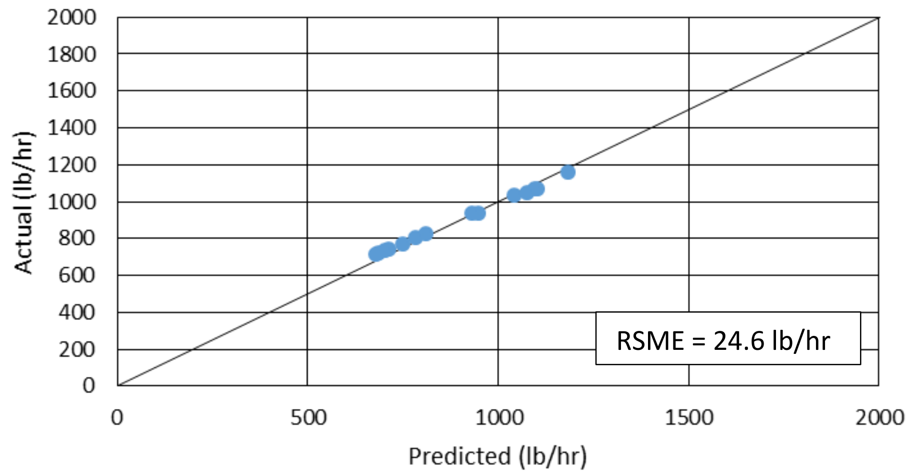

Figure 20. UH-60A Fuel Flow Actual vs Predicted at 4000 ft, 95 °F and 16,000 lb

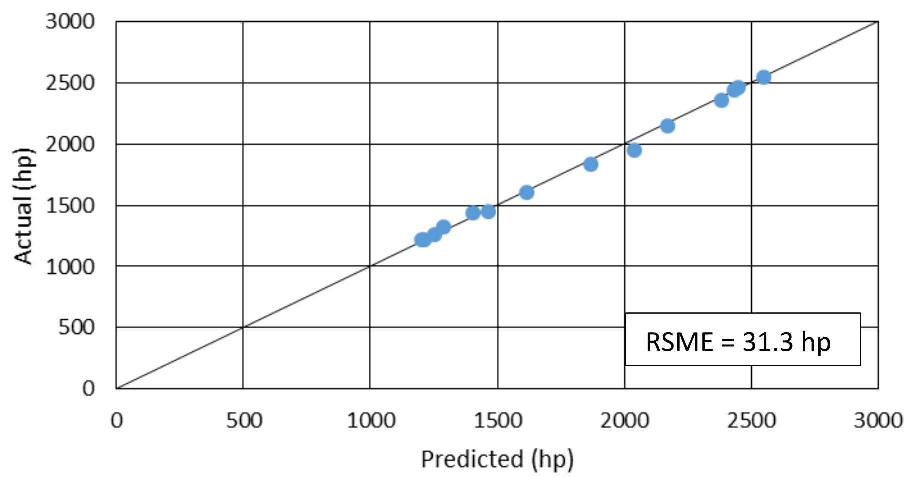

Figure 21. UH-60A Forward Flight Power Required Actual vs Predicted at 4000 ft, 95 °F and 18,000 lb

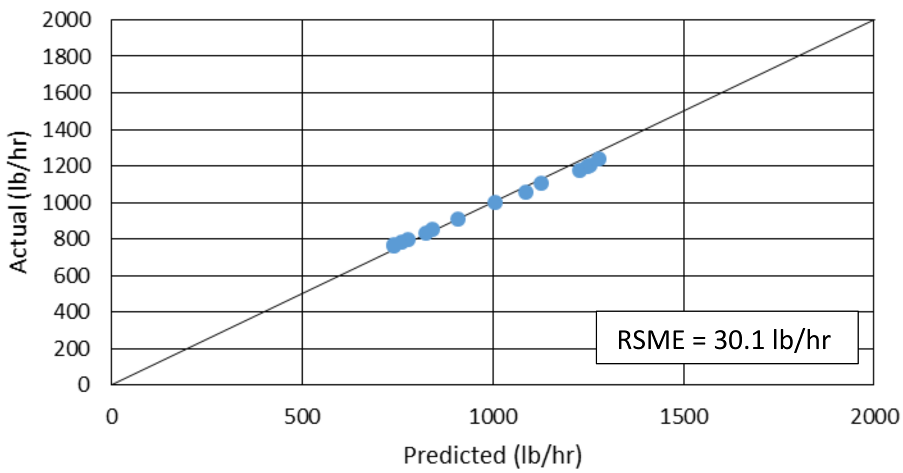

Figure 22. UH-60A Fuel Flow Actual vs Predicted at 4000 ft, 95 °F and 18,000 lb

The NDARC description file output listed the maximum continuous power (MCP) SLS specific fuel consumption (SFC) lower than what is documented by Johnson[20], but Figure 16, Figure 18, Figure 20, and Figure 22, which show the actual by predicted plots for fuel flow, indicate that NDARC's prediction is acceptable. The discrepancy is most likely due to an underestimate of fuel flow at the maximum continuous power setting.

The final step in calibrating the model was to match power available estimates with power available data. In the original calibration, this step was accomplished by picking the referred parameter turboshaft engine model (RPTEM) that most closely resulted in the power ratings of the T700-700 engine. Our options were the generic 2000 hp model provided with NDARC[17] or the RPTEM provided with the NDARC JMR models from previous years. However, this resulted in poor estimates of power available, which was discovered during attempts to predict the UH-60L and UH-60M performance. Currently, NDARC predicts less power available than data in the operator's manual. This will result in an overestimation of engine size during vehicle sizing analysis, and an underestimation of some performance during performance analysis. The performance parameters affected are maximum vertical rate of climb (VROC), absolute and service ceilings, maximum speed, and maximum take-off weight (MTOW). These poor estimates are due to an incorrect lapse rate model. Given the time constraints of the project and the intent to show how to use CATE rather than calibrating a model, the current model was used to move forward with the use case. However, future work on these models will correct this power available error by a similar calibration optimization process discussed above on the relevant RPTEM variables.

2.5.2 Technology Identification and Evaluation

The technologies in Table 8 were identified for modeling because they impact performance, which is easily quantified and evaluated. The table indicates if the technology is installed relative to the UH-60A model.

Table 8: UH-60L and UH-60M Technologies

Technology	UH-60L	UH-60M
GE T700-701C turboshaft engine[23]	Installed	
GE T700-701D turboshaft engine[24]		Installed
Improved Durability Gearbox[25]	Installed	Installed
Wide Chord Blade system[26,27]		Installed

A similar process to last year's method of implementing ARL-VTD technologies was used for analyzing the above technologies, which is represented by Figure 23 below (process given in the 2014 Report). The references given in the Table 8 took the place of the "interfacing with technologists".

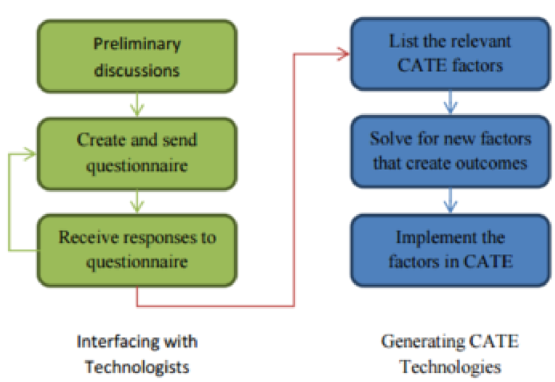

Figure 23. Process for Implementing ARL-VTD Technologies in CATE

For the engines, references 23 and 24 gave values for the weight, engine ratings and fuel consumption. NDARC was coupled with an optimization routine that acted as a numerical solver (selection is arbitrary) to back solve values for CATE's Technology Impact Matrix (TIM). It was assumed each engine had some level of technology that impacted engine weight. After inputting the intermediate rating power (IRP) for the engines into NDARC, an optimization routine was used in which the engine weight technology factor was varied until the output engine weight matched the data. For the GE T700-701C, the calibration factor used for estimating the original T700-700 engine weight resulted in an output engine weight of 457.4 lb, which is close to the 458 lb value given by the technical specifications[23]. For the T700-701D, the optimization routine indicated that the technology of the T700-701D engine resulted in a 3.6% weight decrease. Neither reference indicated changes to the entire propulsion group (changes in nacelle and structural weight), so NDARC parameters relating to these groups were left unchanged. The MCP SLS SFC output from NDARC is not a good indicator of how fuel flow varies with power required, which was described earlier in Section 2.5.1. The technical data on the engines lists the MCP SLS SFC, but we cannot use it because it is a bad indicator. It was assumed that fuel consumption technology would not deteriorate with new engines and that it would be safe to assume no fuel consumption changes. There was not enough information to know how other engine-related weights changed with the upgrade, such as engine supports, nacelle, or exhaust system, so these factors were left untouched. It is recommended that a higher fidelity tool such as NASA's Numerical Propulsion System Simulation (NPSS) be used to provide better inputs into NDARC's RPTEM model.

The information found regarding the improved durability gearbox (IDGB) indicated the increased power rating, but no information about efficiency or weight was found. For performance analysis in NDARC, the IDGB is simply represented by increasing the transmission ratings. For sizing analysis, performance requirements such as MTOW or VROC are used to calculate the drive system rating, so there are no technology impacts to evaluate for CATE's TIM because the TIM is linked to the RSEs for sizing analysis.

A different approach was taken for evaluating the wide chord blade (WCB) system to demonstrate how to make predictions when technology is still being developed. The literature search for the WCB system resulted in two useful sources of information for assessing the new rotor. Yeo et al. modeled the WCB system in a high fidelity code and found that the increase in solidity was the main performance driver because of de-loading the blades[26]. Thus it was assumed that the details of the aerodynamics would be captured by changing blade loading, which is a parameter on the TIM. The 10% increase in solidity reported for the WCB by Yeo et al.[26] results in a 9.1% decrease in blade loading. The solidity increase needs to be converted to blade loading since blade loading is the design parameter used in CATE. Weight changes were based on results from Nixon's paper, which focused on modeling the structure of a composite rotor blade and using optimization to find minimum weight designs. His paper used the UH-60A as a validation case. Nixon's results for estimating blade weight changes due to composite designs were based on the aerodynamics of the UH-60A. Nixon's paper concluded that a single-spar composite design would result in a 21.3% weight reduction and a multi-spar composite design, which would be inherently more ballistically tolerant, would result in a 12.1% weight reduction relative to the metallic design used for the UH-60A[27]. It is assumed that this weight reduction due to composite materials is applicable to the WCB because it uses an all composite blade. Given the year of Nixon's paper (1987), these weight estimates have a good deal of uncertainty. Given the uncertainty in the weight reduction due to composite materials, the wide chord blade technology offers a good case for using distributions bounded by no weight change and a 21.3% weight decrease. However, for cases where distributions cannot be used and because we do not know which structural design was used, the conservative prediction of 12.1% should be selected. There was no specific information found on how the control weight would change, so no assumptions were made as to potential technology impacts for these. Finally, impacts for other technology factors, such as survivability or maintainability, were not researched given the performance focus of the use case. However, future work for demonstrating the maintenance discrete event simulator can use the WCB as an example technology.

Table 9 summarizes the technologies and derived impact relative to the baseline, the UH-60A.

Table 9: Technology Impact Matrix for Black Hawk upgrades relative to the UH-60A

Technology	CWs	TECH_eng	TECH_blade
GE T700-701C turboshaft engine[28]	0%	0%	0%
GE T700-701D turboshaft engine[29]	0%	-3.6%	0%
Improved Durability Gearbox[30]	N/A	N/A	N/A
Wide Chord Blade system[31,32]	-9.1%	0%	-12.1%

2.5.3 NDARC Performance Predictions for UH-60L and UH-60M

CATE is powered by RSEs based on NDARC sizing analyses, so a check on the UH-60L and UH-60M performance calculations in NDARC was performed for comparisons with CATE, presented in later sections. The operator's manual gives information regarding UH-60L fuel flow, allowing a sanity check on the engine fuel consumptions made earlier. The operator manual's data[19] on power required was used to compare our NDARC model predictions. Finally, a Sikorsky mission brief document listed some performance characteristics of the UH-60A, UH-60L, and UH-60M models[33]. This data was used to indicate how close the NDARC performance models represented the various Black Hawk models.

Though there are no technology factors to attribute to the UH-60L model, it is still modeled in NDARC by increasing the engine power available, which also increases the engine weight and represents the T700-701C, and increasing the drive system limit to represent the IDGB. The power required output was compared with data from the operator's manual. Actual by predicted plots were generated used the operator's manual as the actual values and the NDARC model as predicted values. The blue dots are from different velocity points. The same velocities used for calibrating the A model were used here. Figure 25 through Figure 33 indicate how well the UH-60L NDARC model fits the data from the operator's manual.

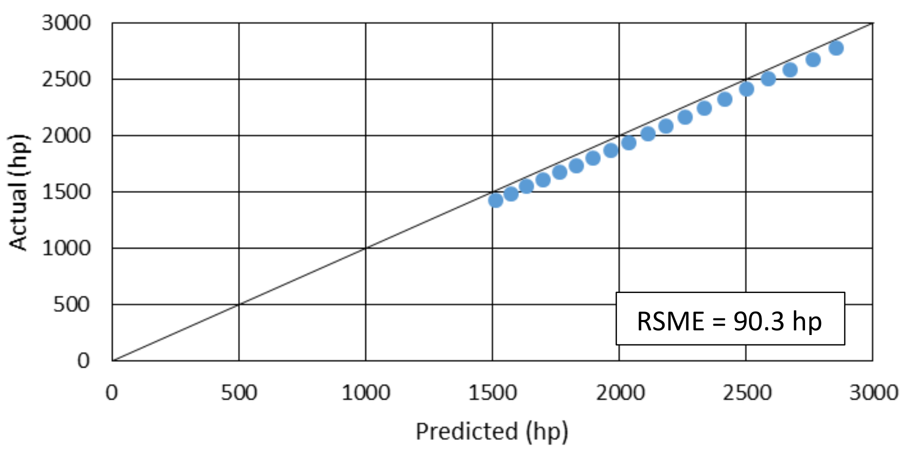

Figure 24. UH-60L Hover Power Required Actual vs Predicted at SLS

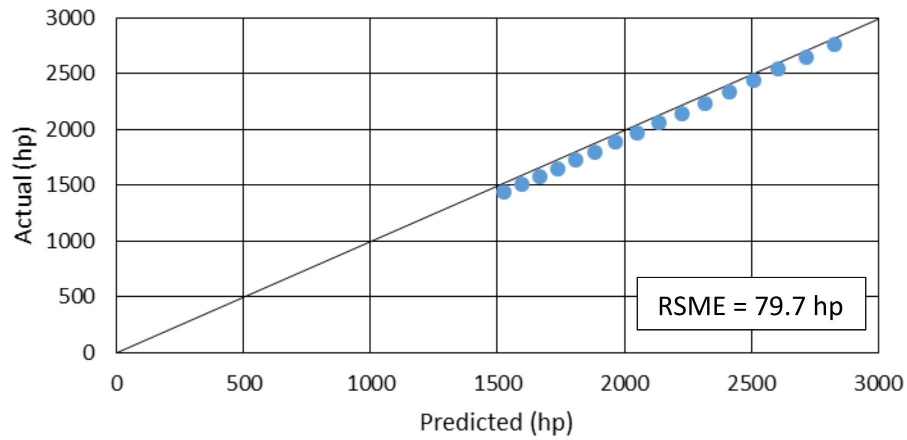

Figure 25. UH-60L Hover Power Required Actual vs Predicted at 4000 ft, 95 °F

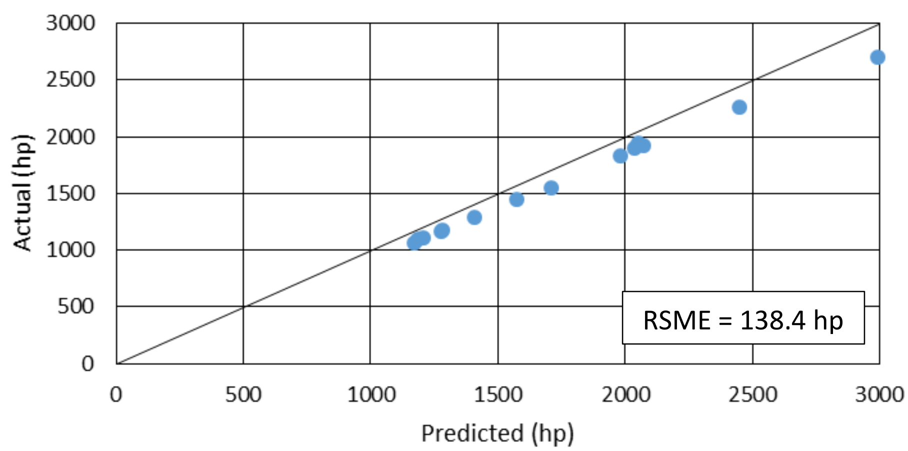

Figure 26. UH-60L Forward Flight Power Required Actual vs Predicted at SLS and 16,000 lb

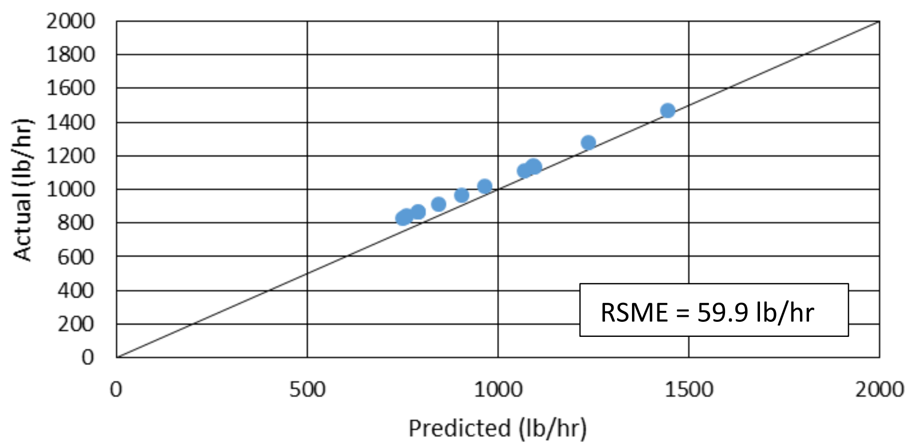

Figure 27. UH-60L Fuel Flow Actual vs Predicted at SLS and 16,000 lb

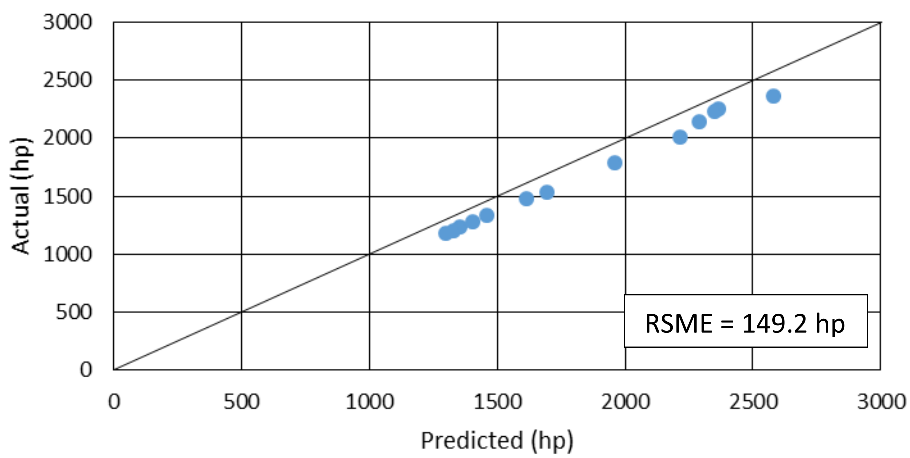

Figure 28. UH-60L Forward Flight Power Required Actual vs Predicted at SLS and 18,000 lb

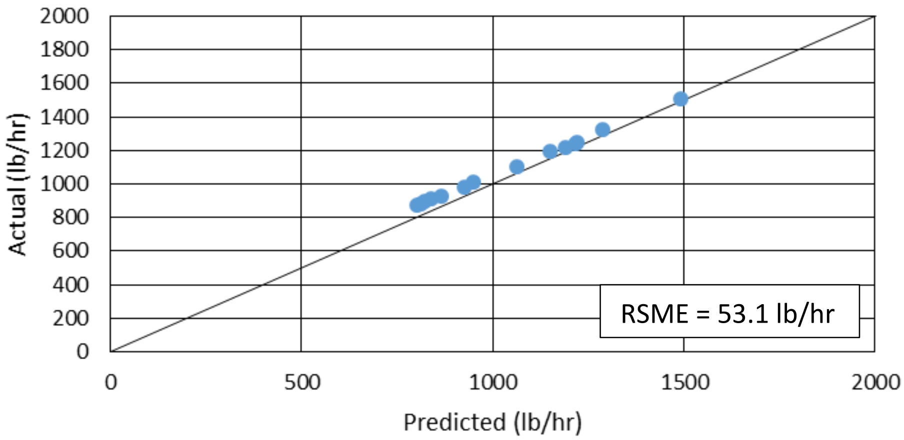

Figure 29. UH-60L Fuel Flow Actual vs Predicted at SLS and 18,000 lb

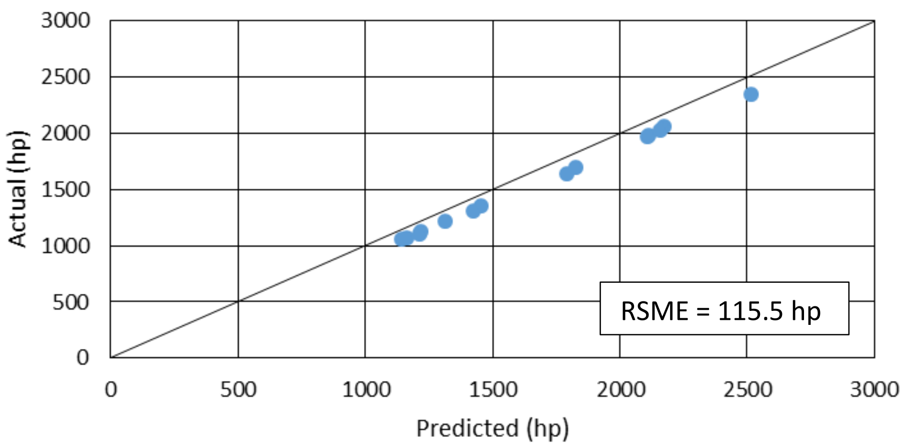

Figure 30. UH-60L Forward Flight Power Required Actual vs Predicted at 4000 ft, 95 °F and 16,000 lb

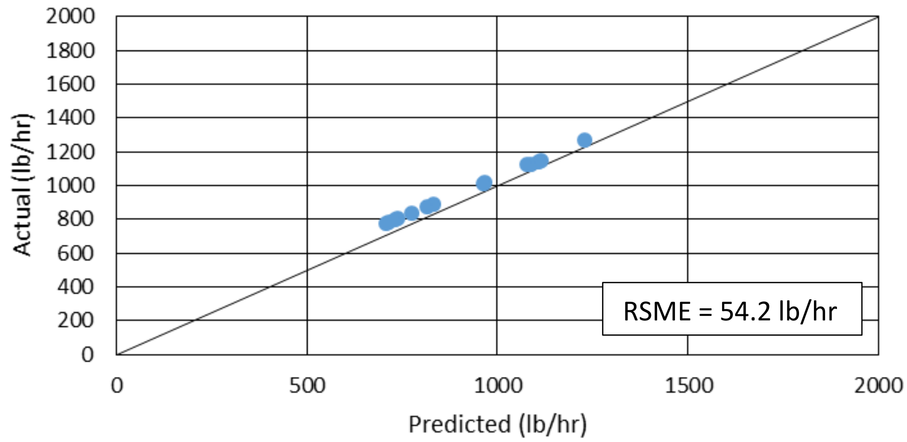

Figure 31. UH-60L Fuel Flow Actual vs Predicted at 4000 ft, 95 °F and 16,000 lb

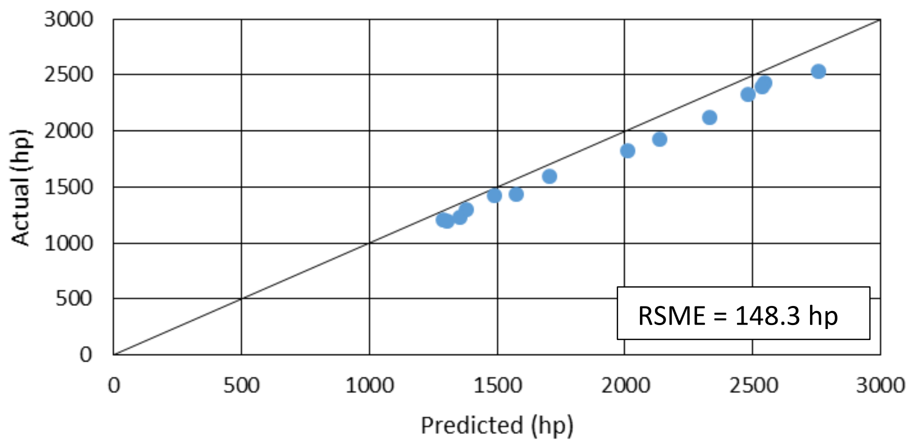

Figure 32. UH-60L Forward Flight Power Required Actual vs Predicted at 4000 ft, 95 °F and 18,000 lb

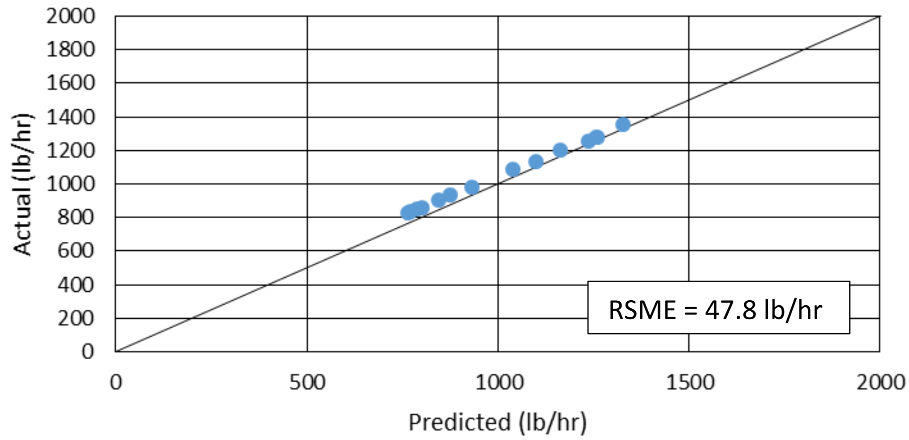

Figure 33. UH-60L Fuel Flow Actual vs Predicted at 4000 ft, 95 °F and 18,000 lb

In general, power required is overestimated, which will cause underestimates for performance calculations for maximum speed, ceilings, hover VROC, or maximum gross weight. NDARC estimates component reference surface area based on weight, so the heavier engine results in more drag, which will cause increased power required. Nothing was known about the drag of the UH-60L, so nothing was assumed. Fuel flow is underestimated, which will cause mission range or endurance to be potentially overestimated. No assumptions were made about fuel flow of the new engine, so the consistent under-estimation indicates that the new engine burns more fuel. It is expected that the RSME will increase other vehicles are modeled. However, as previously mentioned, using a higher fidelity code like NPSS to estimate impacts to input into NDARC should provide a better technology analysis and reduce the error.

Table 10 compares the NDARC weight predictions for selected groups with reported weight values for the UH-60L[34]. Note that no tech factors were changed between the UH-60L and the UH-60A NDARC representation models. The weight groups selected reflect the weight output of CATE. Note that only two technologies were implemented on the UH-60A to represent the UH-60L. Upgrades to avionics, crashworthiness, hover infrared suppression systems, and any other modifications in the block upgrade were not included. The technologies were not included to reduce the scope of the problem. Thus, it is expected that there will be error in the weight estimates. The following table is simply to indicate how the NDARC UH-60L compares with the real UH-60L.

Table 10: NDARC Weight Predictions for the UH-60L

Output Parameter	NDARC Estimate	UH-60L Actual	Error
Rotor Group (lb)	1507.5	1558.3	3%
Empennage Group (lb)	410.8	423.2	3%
Fuselage Group (lb)	1810.0	2416.2	25%
Structure Total (lb)	4486.6	5197.2	14%
Engine System (lb)	1068.5	1204.4	11%
Propulsion Total (lb)	3202.6	3292.8	3%
Empty Weight (lb)	11017.6	12067.5	9%

The large source of error in the fuselage weight drove the high error in structure group weight. Similarly, the engine system weight error drove the propulsion system error. The UH-60L incorporated many things from the variants developed from UH-60A (the Navy and Air Force utility helicopters) in addition to general weight creep, so it is possible that investigating what these changes were and how they affect fuselage weight would allow for better predictions. The error of the engine weight was negligible, as NDARC predicted a weight of 914.9 lb and the data reported a weight of 914.7 lb. The error of the engine system group weight is largely due to underestimating the exhaust system weight by 66.7%. It is likely that an updated hover infrared signature suppressor (IRS) increased the weight of the exhaust system. Information relating to hover IRS is generally restricted so it was not selected as a technology to investigate. More information about technology upgrades will result in better predictions, but there is a point at which the prediction is simply a performance analysis of an existing system. The error in the results above stem from an incomplete representation of the block upgrade. However, the model still allows for inferences about the two upgrades that were applied. This model can be used to answer questions about how a new transmission and engine will affect the useful load of the black hawk helicopter.

To represent the UH-60M, the UH-60L file was modified. Similarly for the UH-60L, the engine available power was increased and the -3.6% technology factor was applied to the engine technology factor to represent the T700-701C. Additionally, the rotor blade loading was decreased by 9.1% and the main rotor weight technology factor was decreased by 12.1%. No other changes were made to represent the UH-60M.

Table 11 gives the results of the NDARC performance prediction of the UH-60A, UH-60L, and UH-60M along with the published results from a pamphlet[33]. Data on the UH-60M similar to the data used for the UH-60L and UH-60A is not available to use for comparisons, so this pamphlet was used instead. The VROC and maximum speed performance estimates are for a gross weight of 16,800 lbs at 4000 ft, 95°F. For VROC, maximum available power is 95% IRP and for maximum speed, maximum available power is 100% MCP. The pamphlet lacks a significant amount of data about the conditions of the performance points. However, it was used across all vehicles so that "apples and oranges" are not compared.

Table 11: NDARC Performance Analysis of UH-60A, UH-60L, and UH-60M vehicles

Model	VROC (ft/min)		V_{cr} (kts)		MTOW (lbs)	
	Data	**NDARC**	***Data***	**NDARC**	***Data***	**NDARC**
UH-60A	*377*	0	*140*	142.5	*20,250*	20,620
UH-60L	*1315*	412.0	*155*	151.0	*22,000*	23,505
UH-60M	*1553*	862.3	*151*	153.0	*22,000*	23,406

There were significant errors in generating estimating the VROC. In the UH-60A case, there was not enough power available to hover at 4000 ft, 95 °F, returning 0 for VROC and indicated that power available was exceeded. The low estimates of VROC are due to NDARC estimates of power available, which are approximately 30% lower than what was available according to the UH-60A operator's manual in the case of the UH-60A and UH-60L estimates. Further investigation and refinement of the model should be done to correct this. Interestingly, NDARC has a decent estimate of maximum speed and overestimates the MTOW for all cases. For the maximum speed, NDARC is correctly giving power available due to ram effects increasing power. For the overestimates of MTOW, there was a lack of information relating to the environmental condition in the pamphlet. In the operator's manual, the closest condition for reaching the UH-60A max weight was SLS and at 100% IRP or the drive limit. Without knowing the MTOW conditions for the pamphlet's data point, it is difficult to make conclusions regarding the accuracy of NDARC's predictions. Additionally, it is unknown if MTOW is limited by structural safety margins. However, the NDARC predictions do agree with the trends between the models. The VROC increases for each new model while the maximum speed and MTOW only see real increases between the UH-60A and the UH-60L models. Technology prediction focuses on the changes between models since models are inherently wrong. The previous table indicates that the technology analysis and modeling environment is capturing these changes, meaning that this NDARC method is acceptable to use in a vehicle development scenario.

Though the calibrated UH-60A model failed to predict power available correctly, it was decided that the project should move forward as there was significant work to be done in creating surrogate models (covered Section 2.2.2) and creating a CATE spreadsheet tool for the UH-60A. Though the results may not be accurate, the use case still demonstrates how the tool can be used alongside the development of a vehicle. Additionally, the surrogate models are made from the NDARC sizing mode to allow many different single main rotor vehicles to be estimated.

2.5.4 CATE Use Case

The following section will demonstrate using the CATE tool. First, representing the three different Black Hawk models in CATE will be discussed. Second, inserting the technologies for the UH-60M into the Interactive Reconfigurable Matrix of Alternatives (IRMA) and assigning their technology factors will be walked through. Finally, the uncertainty of the WCB technology will be used to show how to use the Uncertainty tab in CATE.

However, before digging into the use case, it is relevant to discuss how CATE handles vehicle assessment. CATE is powered by a surrogate model of the design space based around some vehicle type, such as single main rotor or tilt-rotor. In the following discussion, the design space is based on the UH-60A. The effort discussed in Section 2.5.1 was to create a model in NDARC that approximated the performance of the UH-60A. The performance analysis is where design parameters like disk loading and blade loading, vehicle weight, transmission limits, and engine size are input and the mission and performance characteristics are calculated. Sizing analysis is where design parameters, mission characteristics, and performance characteristics are input and then the overall vehicle weight, transmission limits, and engine size are calculated. The design space is created by varying the design parameters and mission and performance specifications. This design space can be represented in CATE by a surrogate model for rapid vehicle assessment.

In CATE, some of the design variables are technology factors, allowing CATE to quickly size vehicles for different sets of technology factor values. For technology investigations, the implication is that CATE re-sizes a vehicle for the selected technology package, and thus outputs new vehicle weight and engine size values. There is no performance boost or detriment from these new technologies, rather the entire vehicle is smaller or larger. This is what is meant by sizing or re-sizing analysis.

In the case that the investigator would rather know the performance boost of technologies, a new tab has been developed to do “baseline + upgrade” analysis in CATE, which is described in Section 2.3. This analysis is the same as the analysis in Section 2.5.3 where the predictions about the UH-60L and UH-60M were made based on the NDARC UH-60A model. While working through the use case, researchers realized that the output needed to show both baseline performance and upgrade performance for the tab to give meaningful results. Additionally, the tab in its current form does not allow all of the design parameters from the dashboard to be changed or the engine rating or drive system limit to be increased. Unfortunately, this was realized too late to incorporate for this year due to the time it took to calibrate the NDARC model, generate the surrogate model, and work out bugs in transferring the UH-60A surrogate model into CATE. Adding this capability in should not be a difficult task. However, without these features, including the “baseline + upgrade” capability does not offer any significant discussion points for the use case. Future work involving the use case will need to take advantage of the “baseline + upgrade” capability to have meaningful results.

4.5.2.1 UH-60A, UH-60L, and UH-60M Representation in CATE

The following section serves to demonstrate how CATE could be used in a vehicle’s development over time. The inaccuracy of the NDARC model will be present in CATE because it is powered by NDARC. However, this just means that the reliability of CATE is dependent on how well the NDARC model captures the vehicle and how well technologies are analyzed. In assessing technologies in these environments, the point is not to be absolutely certain of an impact, but rather to increase knowledge about changes in a vehicles capability. In the following discussions, the “change” that results due to a technology is focused on. Also, the bulk of time in this step is creating the spreadsheet tool, which provided many lessons learned about the surrogate modeling process and about the difficulties in making a new CATE spreadsheet tool. The actual analysis presented below can be accomplish in approximately 30 minutes.

As discussed previously, CATE holds the vehicle design space based on the UH-60A. Representing the UH-60A in CATE is accomplished by inputting the appropriate design parameters, technology factors, and mission and performance values. Researchers determined that these “appropriate” inputs would be those that match values from the data used to calibrate the vehicle[18, 19, 20, 21] or, in the case of the mission and performance values, the output of the NDARC performance analysis.

Table 12 gives the design parameters and technology factors used to approximate the UH-60A in CATE. Figure 34 shows what the CATE section on design parameters and technology factors looks like to approximate the UH-60A with values taken from Table 12. Approximation is necessary because the slider bars currently discretize the variable ranges, so dialing the bar in to an exact number is not always possible.

Table 12: UH-60A Design Parameters and Technology Factors

Blade loading (C_w/σ)[20]	0.0869
Disk loading (lb/ft^2)[20]	7.29
C.G. location[18]	0.0721
Main rotor V_{tip} (ft/sec)[20]	725
Fuselage CD[20]	0.00739*
CD ff[20]	0.00744*
CD V fus[20]	0.391*
CD MR hub[20]	0.00258*
CD MR pylon[20]	0.0359*
CD TR hub[20]	0.0305*
Tech drag MR	0.9**
Tech drag TR	0.9**
Engine[21]	1.43*
TECH_gb[21]	0.850*
TECH_rs[21]	1.25*
TECH_ds[21]	0.875*
Fuselage Body[21]	0.956*
Rotor Blade[21]	1.021*
Rotor Control RWfc_b[21]	0.589*
Rotor Control RWfc_mb[21]	1.05*
Rotor Control RWhyd[21]	0.665*
Engine Pacc_0[21]	50
Engine SP0C_tech[19]	108*
Engine sfc0C_tech[19]	0.458*

*Solved for value by matching output with data

**No reference, default value

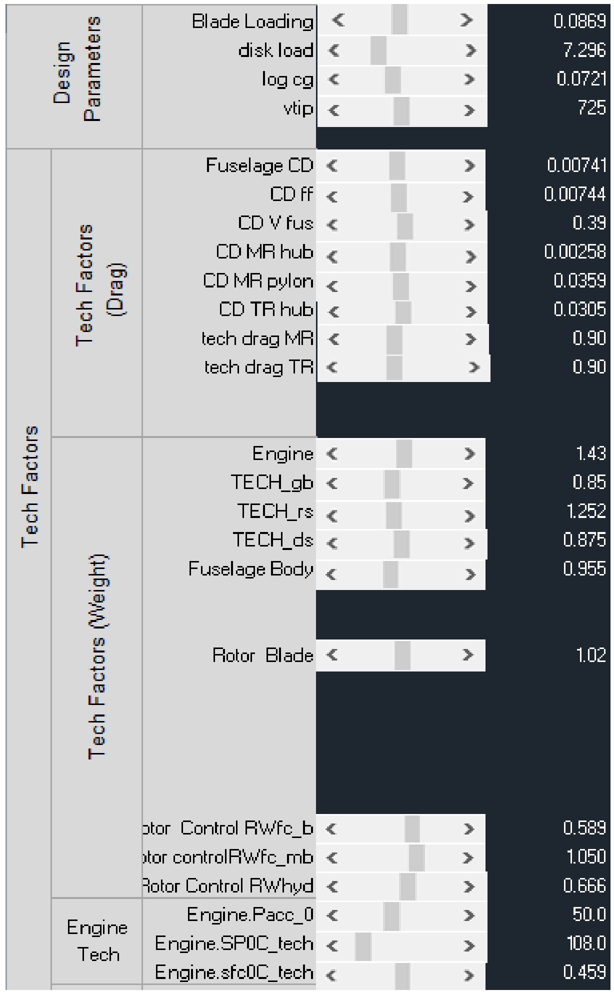

Figure 34. CATE Design Parameters and Technology Factors for UH-60A

Table 13 gives the mission and performance specifications for the UH-60A. All values except for VROC are taken from the NDARC performance analysis to “re-create” the UH-60A NDARC model. The VROC speed is set to the minimum value of the surrogate model’s input range. The ranges are limited because the model fit is significantly improved for smaller variable ranges. Figure 35 shows what the CATE section on sizing conditions and mission parameters looks like to approximate the UH-60A with the values taken from Table 13.

Table 13: UH-60A Sizing and Performance Input

Engine sizing altitude (ft)	4000*
Engine sizing temperature (°F)	95*
VROC (ft/min)	300
Vfwd (kts)	142.5
Design mission hover time (min)	20
Design mission cruise time (min)	83.43
Design mission payload (lb)	2640
Crew Weight (lb)	725**
Fuel tank mission hover time (min)	20
Fuel tank mission cruise time (min)	87.25

*Altitude where engine limits performance

** From Reference 21

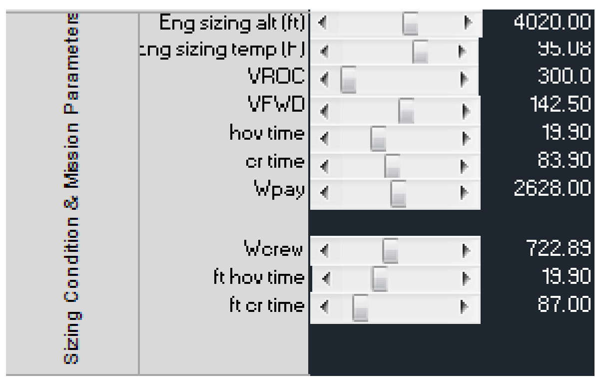

Figure 35. CATE Sizing and Performance Input for UH-60A

The surrogate output for the above sets of inputs is compared with NDARC and real values, where available, in Table 14. The NDARC values are from the sizing analysis performed by CATE for the "NDARC Sizing Verification" portion of the dashboard. These are included to indicate how well CATE fits NDARC. The real data is compared with CATE because technology investigators using CATE will likely be working with CATE outputs rather than NDARC analyses. Cost data is not given because the NDARC cost model was not calibrated as it was out of scope. Future work on this use case could involve using the discrete event simulator to make maintenance cost predictions alongside NDARC's acquisition cost model. Large errors are expected because the CATE analysis is a sizing analysis.

Table 14: Comparison of CATE Output for the UH-60A

Output Parameter	CATE Prediction	NDARC Prediction	UH-60A Value	CATE Error with NDARC	CATE Error with Data
Design Gross Weight (lb)	17702.55	17096.47	16110.2[21]	3.55%	9.88%
Structural Design Gross Weight (lb)	17577.88	17699.80	16825[20]	0.69%	4.47%
Empty Weight (lb)	11132.54	11036.01	10478.6[21]	0.87%	6.24%
Fuel Weight (lb)	2600.89	2498.92	2338[21]	4.08%	11.24%
Operating Weight (lb)	12164.38	11969.61	11412.2[21]	1.63%	6.59%
Useful Load (lb)	6228.14	6060.47	5631.6[21]	2.77%	10.59%
Propulsion Group Weight (lb)	3106.74	2997.09	2874.6[21]	3.66%	8.08%
Empennage Weight (lb)	411.60	398.13	389.5[21]	3.38%	5.67%
Engine System Weight (lb)	1134.07	1099.09	984.2[21]	3.18%	15.23%
Fuselage Group Weight (lb)	1933.75	1910.00	1707.5[21]	1.24%	13.25%
Rotor Group Weight (lb)	1635.72	1578.68	1507.5[21]	3.61%	8.51%
Structure Weight (lb)	4754.41	4684.49	4276.2[21]	1.49%	11.18%
Main Rotor Radius (ft)	27.75	27.31	26.83[20]	1.62%	3.43%
Main Rotor Solidity	0.08	0.08	0.083[20]	0.00%	3.61%
Aircraft Drag (ft^2)	25.87	25.27	25.69[20]	2.39%	0.70%
Fuselage Drag (ft^2)	5.37	5.29	5.28[20]	1.50%	1.70%
Main Rotor Hub Drag (ft^2)	6.24	6.05	5.83[20]	3.28%	7.03%
Main Rotor Pylon Drag (ft^2)	4.17	4.01	4.14[20]	4.05%	0.72%
Drive System Limit (hp)	2832.45	2997.09	2828[20]	5.49%	0.16%
MRP (per engine) (shp)	2129.09	2019.09	N/A	5.45%	
IRP (per engine) (shp)	1988.74	1886.03	1560[20]	5.45%	27.48%
MCP (per engine) (shp)	1678.17	1591.51	1313[20]	5.44%	27.81%
MCP SLS sfc	0.47	0.46	0.474[20]	3.12%	0.84%

From the above table, the error of the CATE output relative to the NDARC output is below 6%, indicating that the surrogate model is accurately reflecting the NDARC model. However, the error of the CATE output to the real data is above 10% for fuel weight, useful load, engine system weight, fuselage group weight, structure weight, and the IRP and MCP engine ratings. Because CATE is powered by NDARC, errors and assumptions in the NDARC UH-60A model help explain the large differences. CATE is also sizing a vehicle, which introduces further error in the weight predictions. The engine rating errors are high given the difficulties in calibrating the power available for the NDARC model. CATE doesn't allow the input of "0" VROC, so the minimum VROC setting is driving the engine to be higher because of power available. This can explain many of the errors in estimating the group weights. NDARC estimates engine weight based on a regression using engine rating, so a higher engine rating will cause a higher engine system weight. A weight increase in one area will cause the entire vehicle to grow larger in a sizing analysis, so the other weight errors are likely due to the increased engine size. Additionally, the engine rating errors are close to 30%, which is approximately how far off NDARC power available estimates were when using the NDARC performance models to predict VROC, maximum speed, and MTOW. Interestingly, the empty weight estimate error is relatively low. For technology investigation, the impact on empty weight from higher engine weight estimates will be mistakenly large.

Representing the UH-60L in CATE follows the same approach as for the UH-60A. In Section 2.5.2, it was determined that the new engine upgrade and transmission upgrade were not associated with any technology factors. Therefore, the design parameters and technology factors for the UH-60L are the same as for the UH-60A. However, the UH-60L has different performance characteristics than the UH-60A due to its upgrades, the T700-701C and the IDGB. To represent the UH-60L in CATE, instead of giving the details of the new upgrades, CATE is given the performance capabilities it should have with the new technologies. Using this information, CATE estimates how much power the new engine should have and what the drive system rating should be. To know what these performance attributes should be, it is necessary to use a tool like NDARC to first predict the performance. This is because of the sizing analysis that CATE is doing. Future CATE versions will simplify this process by allowing users to input engine power ratings and transmission ratings and CATE will run NDARC and predict performance impacts.

The mission and performance specifications to input into CATE are generated using the NDARC VROC and maximum speed values from Table 11. The NDARC values are used since this step is a predictive step. These specifications for the UH-60L are listed in Table 15. Figure 36 indicates the approximate input into CATE because the slider bars do not allow the exact values to be input.

Table 15: UH-60L Sizing and Performance Input

Engine sizing altitude (ft)	4000*
Engine sizing temperature (°F)	95*
VROC (ft/min)	412
Vfwd (kts)	151
Design mission hover time (min)	20
Design mission cruise time (min)	83.43
Design mission payload (lb)	2640
Crew Weight (lb)	725**
Fuel tank mission hover time (min)	20
Fuel tank mission cruise time (min)	87.25

*Altitude where engine limits performance

** From Reference 34

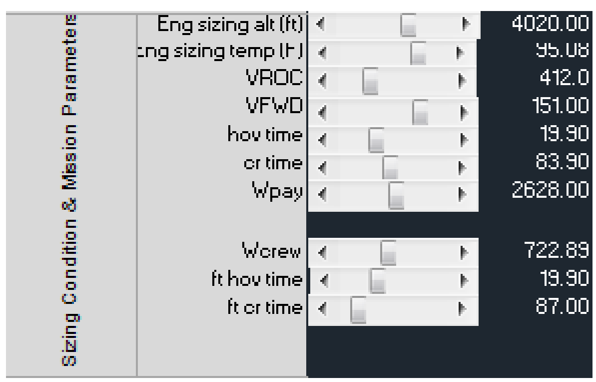

Figure 36. CATE Sizing and Performance Input for UH-60L

Similarly as for the UH-60A, the surrogate output for the UH-60L representation are compared with NDARC and real values, where available, in Table 16. The NDARC values are from the sizing analysis performed by CATE for the "NDARC Sizing Verification" portion of the dashboard. These are included to indicate how well CATE fits NDARC. The real data is compared with CATE because technology investigators using CATE will likely be working with CATE outputs rather than NDARC analyses.

Table 16: Comparison of CATE Output for the UH-60L

Output Parameter	CATE Prediction	NDARC Prediction	UH-60L Value	CATE Error with NDARC	CATE Error with Data
Design Gross Weight (lb)	17957.19	17410.34	17978[34]	3.14%	0.12%
Structural Design Gross Weight (lb)	17958.91	18323.81	N/A	1.99%	
Empty Weight (lb)	11511.72	11323.25	12067.5[34]	1.66%	4.61%
Fuel Weight (lb)	2574.19	2525.53	2338[34]	1.93%	10.10%
Operating Weight (lb)	12502.87	12256.85	13000[34]	2.01%	3.82%
Useful Load (lb)	6232.28	6087.10	5910.5[34]	2.39%	5.44%
Propulsion Group Weight (lb)	3254.20	3120.35	3292.8[34]	4.29%	1.17%
Empennage Weight (lb)	425.86	406.14	423.2[34]	4.86%	0.63%
Engine System Weight (lb)	1201.13	1168.72	1204.4[34]	2.77%	0.27%
Fuselage Group Weight (lb)	2014.37	1980.05	2416.2[34]	1.73%	16.63%
Rotor Group Weight (lb)	1674.55	1617.39	1558.3[34]	3.53%	7.46%
Structure Weight (lb)	4966.75	4834.92	5197.2[34]	2.73%	4.43%
Main Rotor Radius (ft)	27.99	27.56	26.83[20]	1.56%	4.32%
Main Rotor Solidity	0.08	0.08	0.083[20]	0.00%	3.61%
Aircraft Drag (ft^2)	26.76	25.97	N/A	3.04%	
Fuselage Drag (ft^2)	5.45	5.37	N/A	1.49%	
Main Rotor Hub Drag (ft^2)	6.35	6.16	N/A	3.08%	
Main Rotor Pylon Drag (ft^2)	4.29	4.04	N/A	6.19%	
Drive System Limit (hp)	2974.17	3120.35	3400[25]	4.68%	12.52%
MRP (per engine) (shp)	2337.46	2231.60	1890[23]	4.74%	23.68%
IRP (per engine) (shp)	2183.37	2084.54	1800[23]	4.74%	21.30%
MCP (per engine) (shp)	1842.41	1759.02	1662[23]	7.24%	10.85%
MCP SLS sfc	0.47	0.46	0.459[23]	1.30%	2.40%

In Table 16, the error between CATE and NDARC outputs is not larger than 7.24%, which is still an acceptable approximation for technology investigations because the difference due to upgrades is the intent. The error between CATE and data is over 10% for fuel weight, fuselage weight, and the engine power ratings, which is expected due to the inaccurate NDARC model and because there were several technologies not modeled. The mission segments driving the fuel weight did not change between the UH-60A and the UH-60L. Previously, it was assumed that the UH-60L would retain the same mission range capability as the UH-60A. The CATE sizing analysis let the design gross weight increase. In sizing, because the vehicle is larger, more fuel is required. Mission analysis of the UH-60L using the NDARC UH-60L performance analysis could be used to correct this fuel in future iterations of the use case. This larger size is also driving the other overestimated weight groups due to interactions in sizing analysis.

There are two methods for representing the UH-60M. The first is to change inputs on the dashboard to reflect the new technologies. The second is to insert the new technologies on the IRMA and perform analyses using that tab’s output. This requires inserting technologies, which is covered in the next section. The following discussion is about using the dashboard for the UH-60M.

The process for representing the UH-60M will be similar to the representing the UH-60A and UH-60L. The general process is to input design parameters, technology factors, and mission and performance specifications into CATE, then check the output with known data. However, data on the UH-60M other than what is given in the pamphlet[33] is not available, so the accuracy of the prediction is unknown.

The inputs for the UH-60M are the same as the previous inputs for the UH-60L except for technology impacts and the VROC and maximum speed specifications from the NDARC performance analysis. The increased VROC and maximum speed specifications will increase the power of the installed engine. Changing the engine technology factor will account for the technology on the T700-701D that allowed for increased power without increased size. Changing the blade loading and the rotor blade factor will account for the major changes of the WCB. The values for these changes – the engine technology factor, rotor blade technology factor, and blade loading – were evaluated and discussed in Section 2.5.2. The changes are indicated in Table 17, which gives the design parameters and technology factors that correspond to the UH-60M.

Table 17: UH-60M Design Parameters and Technology Factors

Parameter	Value (previous Value)	Technology Impact
Blade loading (C_w/σ)[20]	0.079 (0.0869)	WCB: 9.1% decrease
Disk loading (lb/ft^2)[20]	7.29	
C.G. location[18]	0.0721	
Main rotor V_{tip} (ft/sec)[20]	725	
Fuselage CD[20]	0.00739	
CD ff[20]	0.00744	
CD V fus[20]	0.391	
CD MR hub[20]	0.00258	
CD MR pylon[20]	0.0359	
CD TR hub[20]	0.0305	
Tech drag MR	0.9	
Tech drag TR	0.9	
Engine[21]	1.379 (1.43)	T700-701D: 3.6% decrease
TECH_gb[21]	0.850	
TECH_rs[21]	1.25	
TECH_ds[21]	0.875	
Fuselage Body[21]	1.1	
Rotor Blade[21]	0.897 (1.02)	WCB: 12.1% decrease
Rotor Control RWfc_b[21]	0.589	
Rotor Control RWfc_mb[21]	1.05	
Rotor Control RWhyd[21]	0.665	
Engine Pacc_0[21]	50	
Engine SP0C_tech[19]	108	
Engine sfc0C_tech[19]	0.458	

These values are input into CATE as shown in Figure 37. Values are not exact because the slider bars will not get precise values.

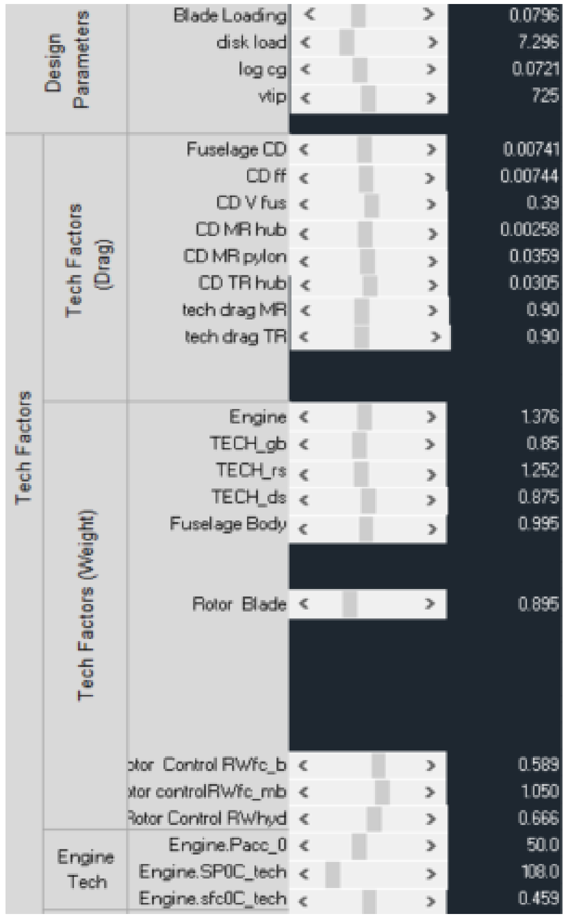

Figure 37. CATE Design Parameters and Technology Factors for UH-60M

The dashboard does not allow specifying the higher engine rating. Similarly to the UH-60L, the predicted performance from NDARC is input to get the higher engine ratings. This includes the increased crew weight and payload for the UH-60M. Table 18 gives these performance values. Additionally, it is assumed that the cruise times are the same as the previous case for the UH-60L. Figure 38 shows the CATE input because slider bars do not allow for exact value entry.

Table 18: UH-60M Sizing and Performance Input

Engine sizing altitude (ft)	4000*
Engine sizing temperature (°F)	95*
VROC (ft/min)	862.3
Vfwd (kts)	153
Design mission hover time (min)	20
Design mission cruise time (min)	67.4
Design mission payload (lb)	3190**
Crew Weight (lb)	980**
Fuel tank mission hover time (min)	20
Fuel tank mission cruise time (min)	75

*Altitude where engine limits performance

** From Reference 33

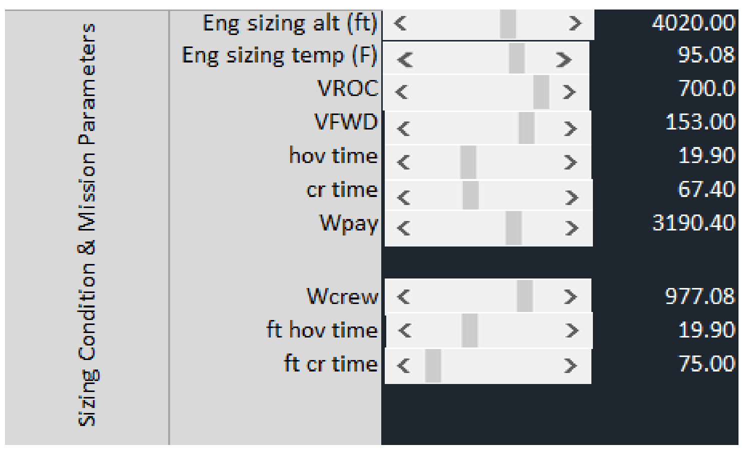

Figure 38. CATE Sizing and Performance Input for UH-60M

The maximum VROC for the surrogate model is 700 ft/min, so the UH-60M value from the NDARC performance prediction cannot be input. Table 19 shows the outputs of CATE and compares them with the NDARC output for the same input.

Table 19: CATE Output for the UH-60M

Output Parameter	CATE Prediction	NDARC Prediction	Error
Design Gross Weight (lb)	21182.34	19901.17	6.44%
Structural Design Gross Weight (lb)	20632.30	20427.66	1.00%
Empty Weight (lb)	13530.47	12775.40	5.91%
Fuel Weight (lb)	3130.48	3001.81	4.29%
Operating Weight (lb)	14578.73	13709.00	6.34%
Useful Load (lb)	7697.57	7125.77	8.02%
Propulsion Group Weight (lb)	3827.32	3566.84	7.30%
Empennage Weight (lb)	520.22	478.98	8.61%
Engine System Weight (lb)	1324.53	1262.10	4.95%
Fuselage Group Weight (lb)	2467.86	2354.08	4.83%
Rotor Group Weight (lb)	2035.51	1853.60	9.81%
Structure Weight (lb)	6029.41	5611.39	7.45%
Main Rotor Radius (ft)	30.45	29.47	3.32%
Main Rotor Solidity	0.09	0.09	0.16%
Aircraft Drag (ft^2)	30.52	28.85	5.76%
Fuselage Drag (ft^2)	5.92	5.73	3.39%
Main Rotor Hub Drag (ft^2)	7.51	7.04	6.72%
Main Rotor Pylon Drag (ft^2)	4.97	4.58	8.50%
Drive System Limit (hp)	3659.13	3566.84	2.59%
MRP (per engine) (shp)	2861.66	2652.69	7.88%
IRP (per engine) (shp)	2673.02	2477.88	7.88%
MCP (per engine) (shp)	2255.58	2090.94	7.87%
MCP SLS sfc	0.45	0.46	1.79%

The errors with NDARC are less than 10%, but the error for this case is worse than the error in the previous models. This is due to more of the values being near the edge of the range used to make the surrogate model. The design of experiments used is more accurate on the interior, so more variables set at “extremes” results in less accurate matches between the surrogate model and the modeling environment. To make inferences about the new technologies, the CATE output for the different models is tabulated and compared in Table 20.

Table 20: Comparison of CATE UH-60M with CATE UH-60L Output and Data

Output Parameter	UH-60L CATE	UH-60M CATE	% Change (CATE values)
Design Gross Weight (lb)	17957.19	21182.34	17.96%
Structural Design Gross Weight (lb)	17958.91	20632.30	14.89%
Empty Weight (lb)	11511.72	13530.47	17.54%
Fuel Weight (lb)	2574.19	3130.48	21.61%
Operating Weight (lb)	12502.87	14578.73	16.60%
Useful Load (lb)	6232.28	7697.57	23.51%
Propulsion Group Weight (lb)	3254.20	3827.32	17.61%
Empennage Weight (lb)	425.86	520.22	22.16%
Engine System Weight (lb)	1201.13	1324.53	10.27%
Fuselage Group Weight (lb)	2014.37	2467.86	22.51%
Rotor Group Weight (lb)	1674.55	2035.51	21.56%
Structure Weight (lb)	4966.75	6029.41	21.40%
Main Rotor Radius (ft)	27.99	30.45	8.79%
Main Rotor Solidity	0.08	0.09	12.50%
Aircraft Drag (ft^2)	26.76	30.52	14.05%
Fuselage Drag (ft^2)	5.45	5.92	8.62%
Main Rotor Hub Drag (ft^2)	6.35	7.51	18.27%
Main Rotor Pylon Drag (ft^2)	4.29	4.97	15.85%
Drive System Limit (hp)	2974.17	3659.13	23.03%
MRP (per engine) (shp)	2337.46	2861.66	22.43%
IRP (per engine) (shp)	2183.37	2673.02	22.43%
MCP (per engine) (shp)	1842.41	2255.58	22.43%
MCP SLS sfc	0.47	0.45	-4.26%

CATE predicts that the UH-60M will see greater than 10% increases an almost all of the outputs with the new performance requirements and technologies. However, some of these increases are due to the significant increases in payload and crew weight causing the vehicle to become larger overall due to sizing analysis. Therefore, it is likely that many of the values are significantly overestimating the actual weights of the UH-60M. Thus, this method of investigating technology impacts would likely give a poor outlook on any technology.

One way to handle this situation is with a “baseline + upgrade” analysis. In this analysis, the technology factors, design parameters, and propulsion limits and power ratings are supplied to CATE which then calculates the new performance of the vehicle. It was attempted to use this capability but it was found to be lacking some necessary functionality to give meaningful results. This was noticed in September and so there was not enough time to fix this.

4.5.2.2 Using the IRMA to Investigate New Technologies

For this analysis, where the focus is not on predicting the UH-60M but investigating the impact of two of its technologies, the starting point is the UH-60L. Representing the UH-60L in CATE is discussed in the previous section.

The two technologies that are investigated for the UH-60M are the T700-701D engine and the WCB system. These technologies and their prediction impacts from Section 2.5.2 are given in Table 21.

Table 21. UH-60M Technologies

Technology	Impact
T700-701D Turboshaft Engine	3.6% engine weight decrease
Wide Chord Blade (WCB)	9.1% blade loading decrease 12.1% blade weight decrease

To input the two UH-60M upgrade technologies, navigate to the IRMA tab and type the technology names into the appropriate rows as shown below in Figure 39.

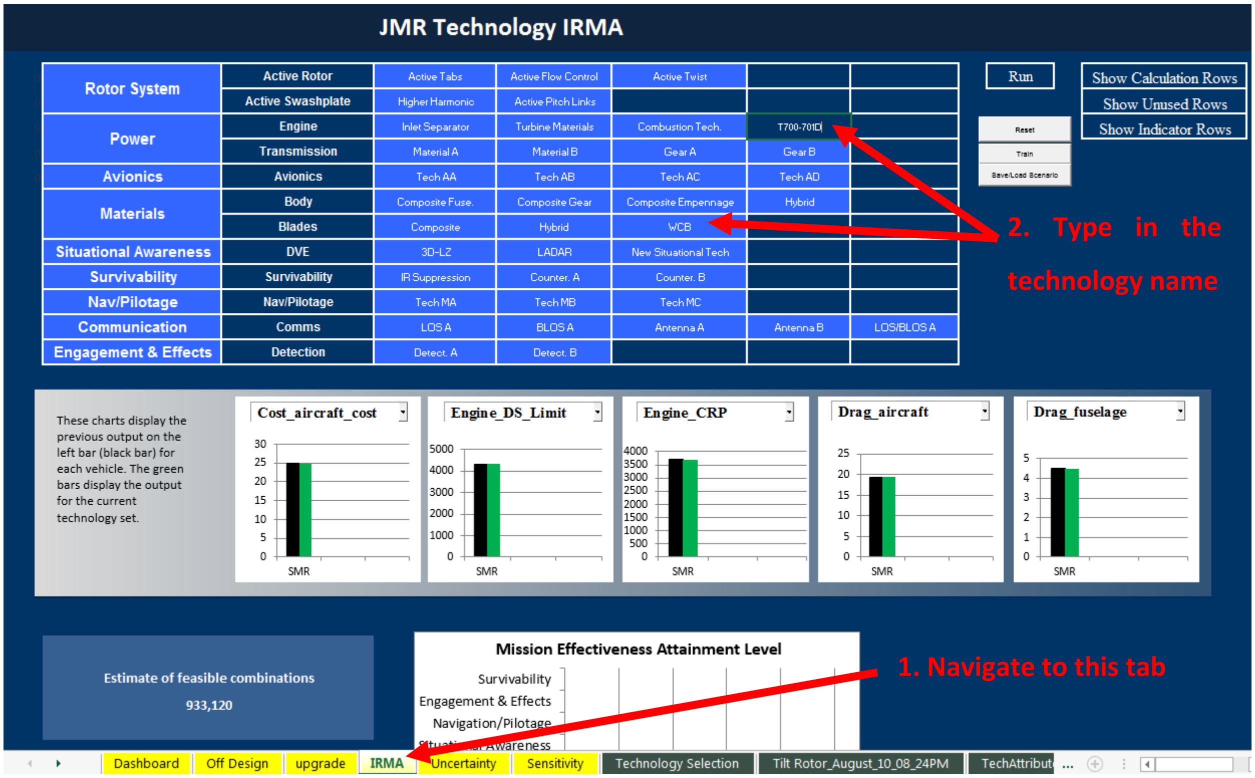

Figure 39. Adding Technologies to the IRMA

The WCB technology is placed in the materials row since it is mainly related to materials. After adding the technology names to the IRMA, their impacts can be added. Navigate to the TechAttributes tab to assign design parameter and technology factor technology attributes in the TIM as shown in Figure 40. In the image, blade loading is "CWs", the engine technology factor is "TECH_eng", and the rotor blade technology factor is "TECH_blade."

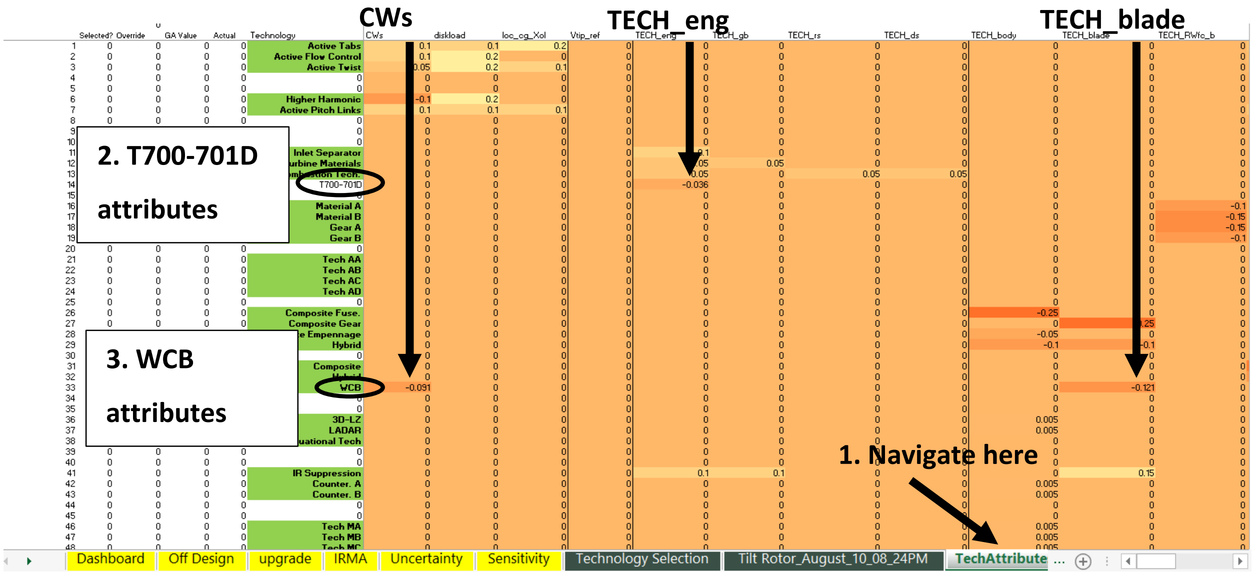

Figure 40. Assigning Technology Attributes

The new technologies will appear in the Technology column. Assigning their attributes is accomplished by typing in the increase/decrease percentage under the column for the variable that is impacted and in the row for the specific technology. For the engine technology, which decreased weight by 3.6%, -0.036 is typed under the TECH_eng column and in the row for T700-701. The conservative weight reduction estimate for the WCB is used, so -0.121 is typed under TECH_blade. Additionally, -0.091 is used under blade loading, the “CWs” tab, to represent the solidity increase.

If the technologies had other effects, such as impacting survivability, then the Mission Effectiveness tab shown in Figure 41 would be used to qualitatively account for such impacts. Refer to the CATE User’s Manual Section 6.2.3 for more information. In the present use case, the two UH-60M technologies are assumed to have no impact on any of the mission effectiveness measures in CATE.

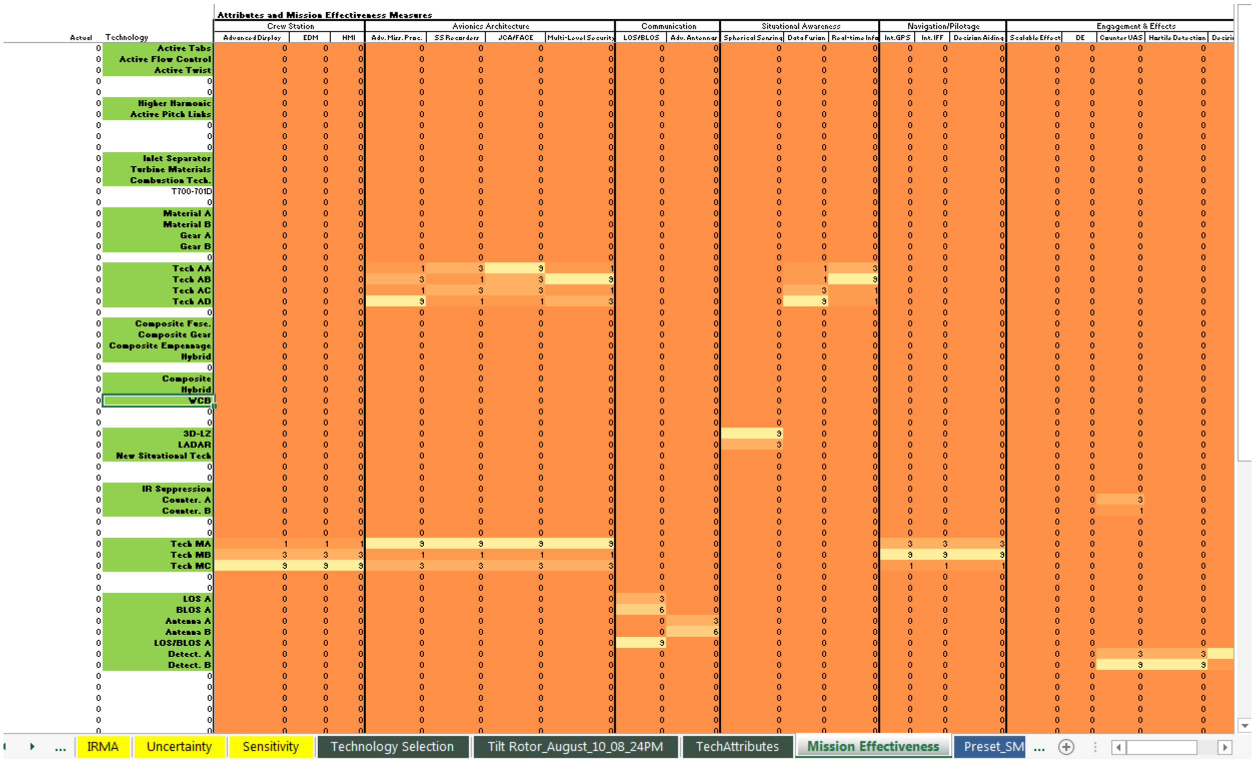

Figure 41. The Technology Mission Effectiveness Tab

After the technology impacts have been assigned in the TIM, they can be analyzed using the IRMA tab. First, click run, and then select a technology and some important outputs to see the effect of installing the technology. When looking at multiple technologies, it is important to note the order in which technologies are selected. In the output graphs, the black bar is the output of the previous technology set, which can be a set with no technologies applied, while the green bar is the result of the currently selected technology set. The application of the engine technology upgrade is shown in Figure 42.

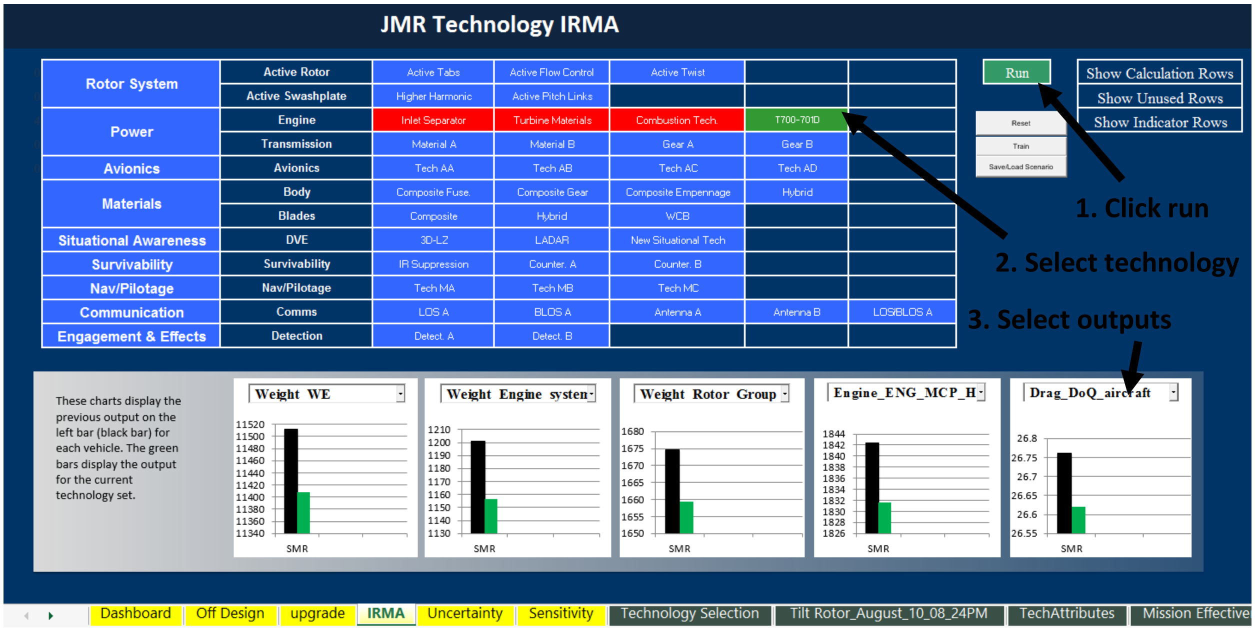

Figure 42. Impact of T700-701D Technology

When selecting outputs to view, only five can be viewed at one time. Currently, CATE users will have to work around this by taking and saving screen shots. For the current use case, empty weight, engine system weight, rotor group weight, engine MCP, and aircraft drag were chosen as the five outputs to look at. The engine system weight, engine MCP, and rotor group outputs allow technology investigators to see how the two UH-60M technologies impact their specific groups. The empty weight and aircraft drag allow investigators to see how the overall vehicle size is affected.

In Figure 42, the engine technology's engine weight decrease appears to lead to an overall smaller vehicle due to the re-sizing analysis that CATE performs. However, the decreases for the rotor group weight, engine power rating, and drag are small. It can be inferred from this that the new engine technology will not give additional benefits other than reducing engine system weight by approximately 50 lb. Or, alternatively, the technology investigator may conclude that a more powerful engine with this weight savings technology can be installed. Predicting the performance result of such an upgrade is the motivation for adding the "baseline + upgrade" capability to see how performance would be affected.

Figure 43 is the impact of the WCB upgrade on the five outputs mentioned above.

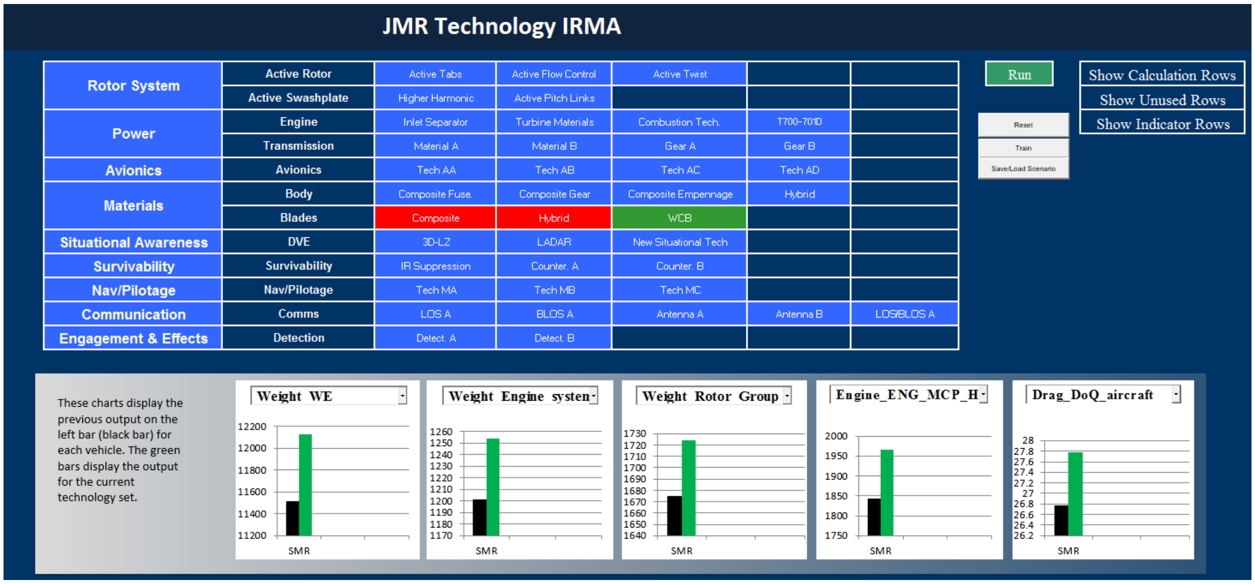

Figure 43. Impact of WCB Technology

CATE predicts that the WCB will increase weight, power, and drag. If technology investigators are analyzing if the weight from increasing solidity with the wider chord will be offset by the composite spar weight savings, CATE gives a clear indication. Technologists may also conclude that improved composite design to further reduce weight needs to be achieved. An additionally interesting effect is how the rotor technology affects the drag and power of the aircraft, whereas the engine technology did not. Though part of this is due to the sizing of the vehicle, increased solidity will increase rotor drag, which would logically require increased power for forward flight. The increase in solidity may have additional performance benefits, such as improved VROC, which is not indicated by CATE with the IRMA analysis. The “baseline + upgrade” capability can be used after it is finished to evaluate the trade-off in performance improvements.

Figure 44 is the impact of both UH-60M upgrade technologies. In Figure 44, the engine technology was selected first and the WCB was selected second.

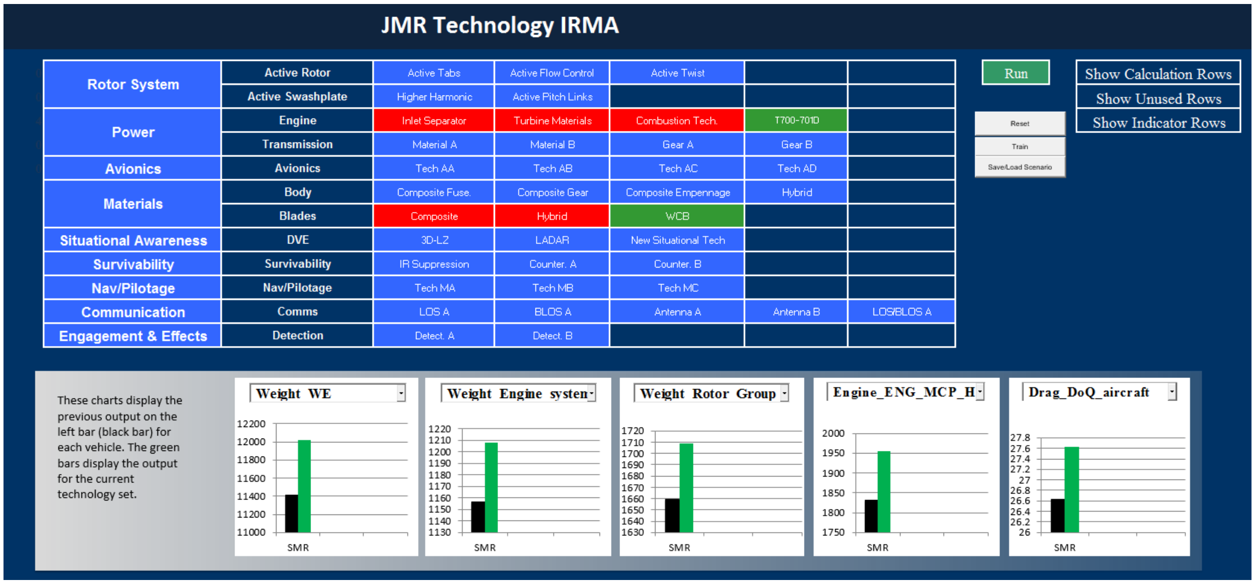

Figure 44. Impact of T700-701D and WCB Technologies

Given the increases seen with just the WCB selected, it is expected that WCB still causes increases because the engine technology did not cause significant reductions. Comparing the output with both technologies selected to the output with only the WCB selected, Figure 43, CATE indicates that the engine technology cannot do much to combat the penalties of the WCB system. This does not indicate that the WCB should not have been fielded, especially given the lack of assessment for other areas it may impact. However, it does indicate that a weight increase can be expected and further investigation of a penalty due to this weight increase should be performed.

As discussed in Section 2.5.2, there is uncertainty in the WCB technology factors because of the time of writing of the Nixon[27] and Yeo et al.[26] reports. The uncertainty tab in CATE provides a quick and simple analysis for capturing this uncertainty.

4.5.2.3 Assessing Uncertainty with CATE

Assessing uncertainty usually involves setting up probability distribution functions (PDF) for the variables that have uncertainty, and then running large Monte Carlo simulations to estimate the distributions on the output of the model. Monte Carlo simulations require a significant amount of runs to be accurate, so models that take even a second to run can take hours for one simulation. CATE's use of surrogate models allow uncertainty simulations to be performed much faster. For a 1000 case simulation, CATE takes approximately 2 minutes. A fast case in NDARC takes about 2 seconds, and most cases are slower. At 2 seconds per case, NDARC would take around 34 minutes. However, factoring in time for parsing and recording data, the NDARC Monte Carlo simulation could take closer to 3 or 4 hours. This section will use the WCB uncertainty to demonstrate how to use CATE's uncertainty analysis capability.

First, PDFs for the WCB technology factors need to be generated. This use case modifies the approach developed by Kirby[35] for evaluating technology (step 7). Kirby gives an equation for determining beta distribution parameters based on TRL. The CATE uncertainty tab currently allows for uniform and normal distributions, so the shape parameter equation was instead used to estimate standard deviation as shown in Equation (1) below. TRL is the technology readiness level and k_i is the technology impact. In general, the percent impact is used rather than actual values.

$$\sigma^2 = \left(0.3 - (TRL - 1)\frac{0.25}{8}\right)k_i \tag{1}$$

In the modified approach, a normal distribution is assumed with technology impact used as the mean. Table 22 from Kirby gives the NASA TRL scale which will be used to associate a TRL with each of the technology impacts for the WCB – the blade loading and the blade weight.

Table 22. Typical Technology Readiness Levels

Level	Readiness Description
1	Basic principles observed and reported
2	Technology concept and/or application formulated (candidate selected)
3	Analytical and experimental critical function or characteristic proof of concept or completed design
4	Component and/or application formulated
5	Component (or breadboard) verification in a relevant environment
6	System/subsystem (configuration) model or prototype demonstrated/validated in relevant environment
7	System prototype demonstrated in flight
8	Actual system completed and flight qualified through test and demonstration
9	Actual system flight proven on operational vehicle

It was assumed that there were two pieces of uncertainty for the WCB upgrade – the solidity increase and the weight decrease.

WCB reports a solidity increase of 10% as documented by Yeo et al, which was written after flight tests of a UH-60A with WCB prototypes and standard blades were performed. Therefore, the technology was at TRL 7 at the time of writing of the Yeo et al paper. A 10% increase in solidity is a 9.1% decrease in blade loading. Plugging the TRL and 9.1% into Equation (1) gives a standard deviation for blade loading to be 1.02%. The standard rotor blade loading is 0.0869, so the WCB blade loading is 0.079, which is used as the mean for the normal distribution. The standard deviation is 1.02% of the mean, or 0.001.

For the weight decrease, the time of writing of Nixon's paper[27] indicates that the WCB TRL was likely to have been a 3 given the analytical nature of the study. Using the 12.1% as the technology impact, Equation (1) gives a standard deviation of 2.87%. The calibrated rotor blade technology factor is 1.02, so the new technology factor is 0.9 which is used as the mean for the normal distribution. The standard deviation is 2.87% of the mean, or 0.026.

For the present discussion, no other uncertainty is assumed. In CATE's uncertainty analysis, distributions are set for all the input variables. To make these a single value, select the uniform distribution option and set the minimum and maximum bounds to be the desired input value.

Figure 45 illustrates what the inputs for the uncertainty tab looks like for the WCB uncertainty analysis.

Inputs

		Helicopter					
				Uniform		Normal	
		Current		Min	Max	Mean	St_dev
0	Eng sizing alt (ft)	4020.0	Unifo	4000	4000		
1	Eng sizing temp (F)	95.1	Unifo	95	95		
2	VROC	412.0	Unifo	300	300		
3	VFWD	151.0	Unifo	145	145		
4	hov time	19.9	Unifo	20	20		
5	cr time	67.4	Unifo	85	85		
6	Wpay	2628.0	Unifo	2640	2640		
7	Wcrew	722.9	Unifo	725	725		
8	ft hov time	19.9	Unifo	20	20		
9	ft cr time	75.0	Unifo	120	120		
10	Blade Loading	0.0869	Norm			0.079	0.001
11	disk load	7.296	Unifo	7.3	7.3		
12	log cg	0.0721	Unifo	0.0721	0.0721		
13	vtip	725.0	Unifo	725	725		
14	Fuselage CD	0.00741	Unifo	0.0074	0.0074		
15	CD ff	0.00744	Unifo	0.006	0.009		
16	CD V fus	0.39000	Unifo	0.39	0.39		
17	CD MR hub	0.00258	Unifo	0.0026	0.0026		
18	CD MR pylon	0.03588	Unifo	0.0359	0.0359		
19	CD TR hub	0.03050	Unifo	0.0305	0.0305		
20	tech drag MR	0.9	Unifo	0.9	0.9		
21	tech drag TR	0.9	Unifo	0.9	0.9		
22	Engine	1.3580	Unifo	1.43	1.43		
23	TECH_gb	0.8500	Unifo	0.85	0.85		
24	TECH_rs	1.2520	Unifo	1.252	1.252		
25	TECH_ds	0.8750	Unifo	0.875	0.875		
26	Fuselage Body	1.1000	Unifo	0.955	0.955		
27	Rotor Blade	1.0200	Norm			0.9	0.026
28	Rotor Control RWfc_b	0.5890	Unifo	0.589	0.589		
29	Rotor controlRWfc_mb	1.0500	Unifo	1.05	1.05		
30	Rotor Control RWhyd	0.6664	Unifo	0.6664	0.6664		
31	Engine.Pacc_0	50.0000	Unifo	50	50		
32	Engine.SP0C_tech	108.0000	Unifo	108	108		
33	Engine.sfc0C_tech	0.4590	Unifo	0.459	0.459		

Figure 45. CATE Uncertainty Tab WCB Inputs

Click Simulate after inputting the number of runs. For this assessment, 1000 runs were chosen as it was felt this would adequately sample the distributions. Users could estimate the necessary amount of runs by "brute force" – increase runs based on how choppy the distributions are sampled. Future research on technology representation and prediction can investigate Monte Carlo simulations and how to determine the optimal number of runs. After clicking "Simulate," CATE builds PDFs for all the inputs and cumulative distribution functions (CDF) for all the outputs. Figure 46 shows the CATE rotor group weight output for the WCB uncertainty assessment.

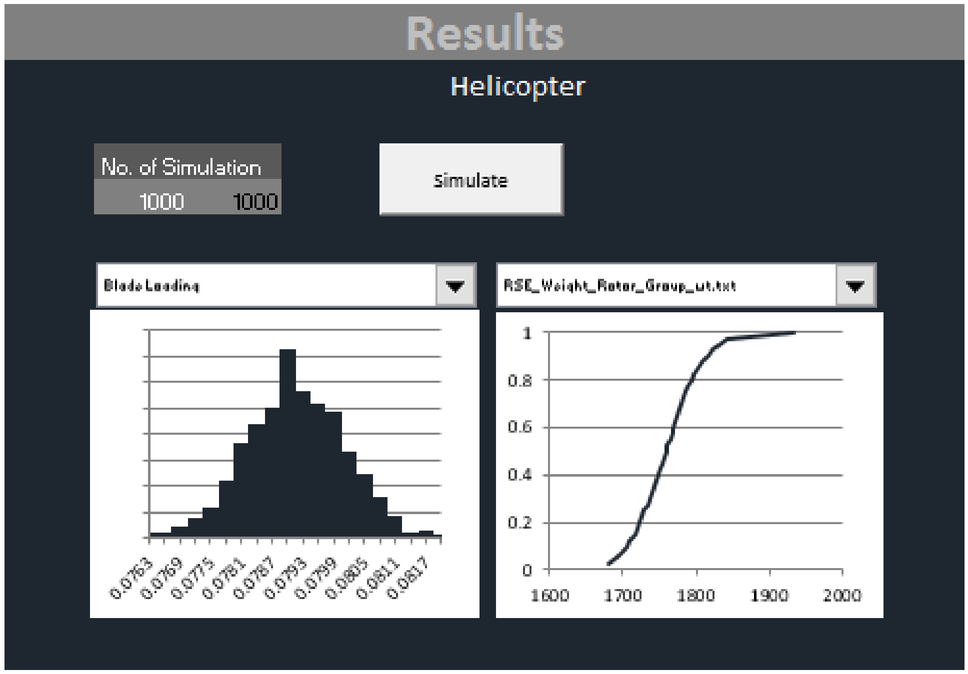

Figure 46. CATE Uncertainty Tab 1000 Simulation Output

In the above figure, the blade loading distribution resembles a “choppy” normal distribution. Increasing the number of simulations to 5000 does not significantly smooth out the distribution or alter the output as shown in Figure 47. Note that in both figures, the number of simulations being performed is in black. In the creation of a CATE environment based on the UH-60A, the removal of the compound and tilt-rotor vehicles caused some assignment issues in CATE, the simulation input field being a minor one.

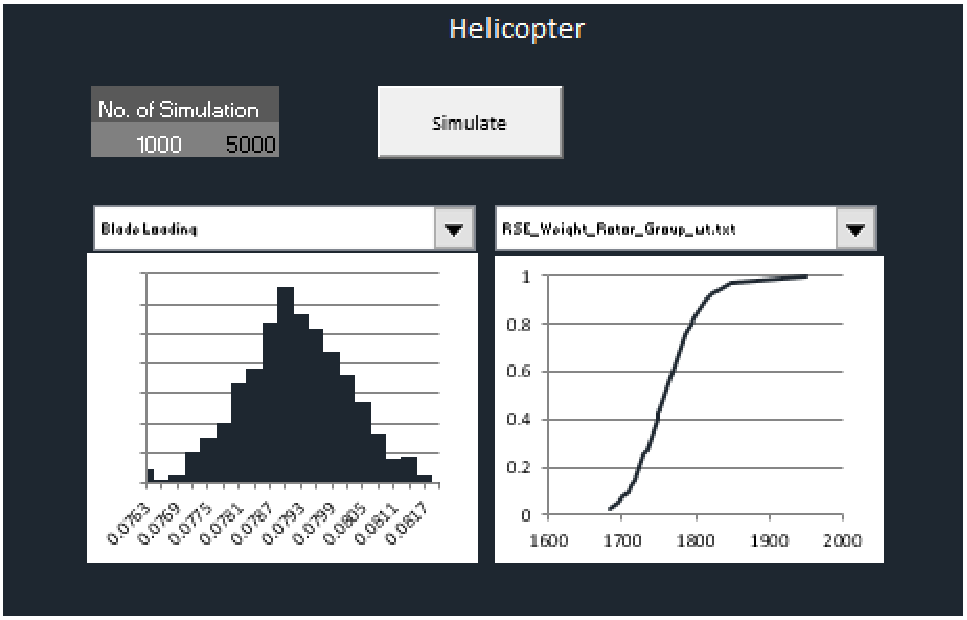

Figure 47. CATE Uncertainty Tab 000 Simulation Output

The CDF for the rotor group weight indicates the percentage of simulations (y-axis) where the rotor group weight (x-axis) was no greater than some value. For example, 80% of the simulations had rotor group weights that were less than 1800 lb. About 30% of the simulations had rotor group weights less than 1750 lb. When selecting the WCB in the IRMA, CATE predicted a rotor group weight near 1720 lb. CATE's uncertainty assessment indicates that 20% of the cases were no greater than 1720 lb, indicating that this weight prediction is unlikely. However, this uncertainty assessment is dependent on the assumptions of the distributions for the technology impacts. If the distribution parameters are agreeable, then it is reasonable to expect heavier blades than what the original technology impacts indicated.

4.5.2.4 Case Study Summary

The previous sections discussed how CATE can be used to represent the UH-60A, UH-60L, and UH-60M by selecting points in the design space and implementing technologies. Additionally, because the use case followed a succession of upgrades, the use case highlighted the difficulties in using a re-sizing analysis to predict the impact of upgrades. The IRMA can only be used to make inferences about technologies, but not give concrete support for or against selecting a technology. One important inference that can be made about technologies is where improvements need to be made. In the case of the WCB, technology investigators could conclude that the weight savings from composites needed to be improved before using the technology. Additionally, the use case showcased an application of the uncertainty analysis, which can be used to support technology impact claims quickly and easily. In the case of the WCB, the uncertainty analysis suggested that the WCB weight savings would be less than the originally predicted 12.1%. Finally, the use case clearly illustrated how a “baseline + upgrade” capability is needed, especially for upgrading existing vehicles. Future work on this use case will involve incorporating the “baseline + upgrade” capability and refining the NDARC UH-60A model.

3. Appendix A – NDARC Calibration Parameters

Table 23: All possible parameters for calibrating NDARC power required output and their range.

NDARC Parameters*	Minimum Value	Maximum Value
MR_tiploss	0.9	0.99
MR_Ki_hover	1	2.25
MR_Ki_climb	1.125	2.25
MR_Ki_prop	1	4
MR_Ki_edge	1	4
MR_Ki_min	1	3
MR_Ki_max	10	20
MR_CTs_Hind	0	0.1
MR_kh2	-99	99
MR_mu_edge	0	0.7
MR_CTs_Pind	0	0.16
MR_ke1	0	1.6
MR_ke3	0	2
MR_Xe	0.1	9
MR_CTs_Dmin	0	0.08
MR_d0_hel	0	0.018
MR_d0_prop	0	0.018
MR_d2_hel	0	1.8
MR_d2_prop	0	1.8
MR_CTs_sep	0	1.2
MR_dsep	0	40
MR_Xsep	0.1	6
MR_fstall	0.1	2
MR_dstall1	0	10
MR_dstall2	0	80
MR_Xstall1	0.016553	4
MR_Xstall2	0.02335	6
MR_Mdd0	0	1.36
MR_dm1	0	0.01
MR_dm2	0	1.8
MR_Xm	0.1	6

NDARC Parameters*	Minimum Value	Maximum Value
TR_tiploss	0.9	0.99
TR_Ki_hover	1	2.25
TR_Ki_climb	1	2.25
TR_Ki_prop	1	4
TR_Ki_edge	1	4
TR_Ki_min	1	3.3
TR_CTs_Hind	0	0.1
TR_kh2	-99	99
TR_mu_edge	0	0.7
TR_ke1	0	1.6
TR_ke3	0	2
TR_Xe	0.1	9
TR_CTs_Dmin	0	0.08
TR_d0_hel	0	0.018
TR_d0_prop	0	0.018
TR_d2_hel	0	1.8
TR_d2_prop	0	1.8
TR_CTs_sep	0	1.2
TR_dsep	0	40
TR_Xsep	0.1	6
TR_fstall	0.1	2
TR_dstall1	0	10
TR_dstall2	0	80
TR_Xstall1	0.1	4
TR_Xstall2	0.1	6
TR_Mdd0	0	1.36
TR_dm1	0	0.01
TR_dm2	0	1.8
TR_Xm	0.1	6

* MR_ and TR_ indicate whether the parameter is for the main rotor or tail rotor, respectively.

Table 24: Selected NDARC Parameters for calibrating power required and their calibration value. Others defaulted to values from NDARC validation[20]

NDARC Parameters*	Calibrated Value
MR_tiploss	0.961
MR_Ki_hover	1.264
MR_Ki_climb	1.719
MR_Ki_prop	2.522
MR_Ki_edge	3.034
MR_Ki_min	1.274
MR_Ki_max	17
MR_kh2	-93.44
MR_mu_edge	0.338
MR_CTs_Pind	0.126
MR_ke1	0.992
MR_ke3	0.326
MR_Xe	3.98
MR_CTs_Dmin	0.08
MR_d0_prop	0.012
MR_d2_hel	1.213
MR_d2_prop	0.102
MR_CTs_sep	0.981
MR_dsep	38
MR_Xsep	5.16
MR_fstall	1.898
MR_dstall1	4.958
MR_dstall2	39.12
MR_Xstall1	2.177
MR_Xstall2	1.621
MR_Mdd0	0.723
MR_dm2	0.923
MR_Xm	2.8

NDARC Parameters*	Calibrated Value
TR_Ki_hover	1.024
TR_Ki_climb	2.249
TR_Ki_prop	2.18
TR_Ki_min	1.191
TR_kh2	73.1
TR_mu_edge	0.292
TR_Xe	5.64
TR_CTs_Dmin	0.048
TR_d0_hel	0.006
TR_d2_hel	0.009
TR_d2_prop	1.166
TR_dsep	25.62
TR_Xsep	2.763
TR_fstall	1.00
TR_dstall1	6.414
TR_dstall2	34.06
TR_Xstall1	1.916
TR_Mdd0	0.429
TR_dm1	0.004
TR_dm2	0.460

* MR_ and TR_ indicate whether the parameter is for the main rotor or tail rotor, respectively.

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